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EXPERIMENTAL EVALUATION
OF JOINT DESIGNS FOR
A SPACE-SHUTTLE ORBITER
ABLATIVE LEADING EDGE

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SUMMARY

Tests have been conducted to evaluate the thermal performance of two types of ablative leading-edge joints for a space-shuttle orbiter: chordwise joints between ablative leading-edge segments, and spanwise joints between ablative leading-edge segments and reusable surface insulation (RSI) tiles. Test models containing such joints were exposed to simulated shuttle heating environments.

For the test conditions of this investigation, the data show that the thermal performance of models with chordwise joints was as good as jointless models in simulated ascent-heating and orbital cold-soak environments. However, none of the joints performed satisfactorily during the simulated entry-heating tests. Additional work is required on the joint seals, and, in particular, on the effects of heat-induced seal-material surface irregularities on the local flow. The effects of downstream deposition of ablation products on the performance of the RSI tiles should also be carefully evaluated.

INTRODUCTION

Studies of the thermal protection system (TPS) for a space-shuttle orbiter generally recommend a passive, nonmetallic TPS for the leading edges. This recommendation applies to both the wing and vertical fin leading edges. The oxidation-inhibited carbon-carbon materials are proposed for the leading-edge TPS. However, state-of-the-art ablation materials may be considered for alternative leading-edge TPS, particularly for the initial flights.

Two recent studies of ablative leading edges have been made. The first was an optimization design study that considered ablative TPS for the entire orbiter. (See ref. 1.) The second was a design study of ablative TPS for the leading edge that also examined the effects of surface roughness and recession on subsonic aerodynamic performance. (See ref. 2.) The latter study was supported jointly by the NASA Langley Research Center and the Johnson Space Center.

Problem areas which require further study include chordwise joints between ablative leading-edge segments, spanwise joints between the ablative leading-edge segments and the reusable surface insulation (RSI) tiles, and the effects of deposition of ablation products downstream on the RSI tiles. The chordwise and spanwise joints were among the design areas of concern in reference 2. Two joints were designed for each area and representative test models were fabricated but not tested during that study. The purpose of this paper is to present the test data obtained with these models. The ablator/ablator joint models were sequentially subjected to simulated ascent-heating, orbital cold-soak, and entry-heating tests. The ablator/RSI joint models were subjected to only simulated entry-heating tests. Based on the test data, the thermal performance of the joint models is evaluated. A qualitative evaluation of the extent of the deposition of the ablation products on the RSI and the effect of the joint seal material on this deposition are presented. A quantitative evaluation of the effects of the downstream deposition on the RSI surface properties is needed before a final leading-edge design can be made.

SYMBOLS

H_{∞}	free-stream enthalpy, J/kg
M	Mach number
p	pressure, atm (1 atm = 101.3 kPa)
p_l	local pressure, atm
p_{∞}	free-stream pressure, atm
q	convective heat-transfer rate, W/m ²
q_2	heat-transfer rate at location 2, W/m ²
R_n	nose radius, cm
R_{∞}	free-stream Reynolds number, cm ⁻¹
S	distance along surface from geometric center line, cm
T	temperature, K

T_2	temperature at location 2, K
T_4	temperature at location 4, K
T/C	thermocouple at locations 1 to 7
ΔT	temperature rise, K
θ	angle between axis of symmetry and surface location on cone, rad

Subscripts:

cw	cold wall based on 290 K
l	local wall value
mp	midpoint
t	total
2	behind shock wave

MATERIALS AND JOINT DESIGN MODELS

The materials selection, design rationale, and trade-offs for the joint designs evaluated in this study are presented in detail in reference 3. Details of the test models of these joints, which consisted of simple 5° beveled butt joints, are shown in figures 1 and 2. The chordwise ablator/ablator joint model is shown in figure 1. Two models of the chordwise joint design, each with a different seal material, were fabricated. The ablation material, described in reference 2, consists of a silicone elastomeric resin which is filled with hollow silica and phenolic microspheres and quartz fibers, reinforced with a phenolic-glass honeycomb. The ablator is a thermally efficient, low-density (497 kg/m^3) material suitable for leading-edge application. A low-density silicone foam and a silica felt were the two materials used for the joint seals. The silicone-foam seal and the silica-felt seal were compressed about 25 percent and 85 percent, respectively, between two pieces of beveled ablation material and the assemblage was bonded to the backup sheet. Thermocouples were located on the metal substructure beneath the joint and ablator. (See fig. 1(b).)

The spanwise ablator/RSI joint models are shown in figure 2. Since this joint would be in a relatively flat portion of the leading edge, flat models were made. The ablation material was the same as that used for the ablator/ablator joint models. The RSI material was a 240-kg/m³ silica material with a borosilicate glass, silicon-carbide pigment coating on the top surface only. The RSI material and coating are described in reference 3. Each model was bonded to a phenolic-glass backup sheet. Slots were cut in the backup sheet to interrupt the lateral heat-conduction path. The models were fabricated with a deliberate rearward-facing step. (See section B-B of model in fig. 2.) This step was included in an attempt to avoid developing a forward-facing step caused by recession of the ablator tile during entry heating. The models have the ablator/RSI joint at a 45° angle to the stream-flow direction in an attempt to simulate the sweep angle and resulting flow conditions on a full-size shuttle-orbiter leading edge. Two types of seals and seal materials were used for this joint: a wavy silicone-rubber seal and a silica-felt seal. The silica-felt material was compressed approximately 85 percent between the RSI and ablator sections and the assemblage was bonded to the backup sheet. Thermocouples were located at the bottom of the joint, and at the back surface of the ablator tile and the RSI tile. (See fig. 2.)

TEST APPARATUS, ENVIRONMENT, AND PROCEDURES

The ablator/ablator joint models were sequentially subjected to simulated ascent-heating, orbital cold-soak, and entry-heating tests. The ablator/RSI joint models were subjected to only simulated entry-heating tests. Ascent heating is negligible at this location on the leading edge and the effects of cold soak on the joints were assumed to be negligible. Since the two types of joint models were subjected to very different test environments, the test apparatus, the test environment, and the test procedure used for each type are discussed separately.

Test Apparatus

Ablator/ablator joint model.- The simulated ascent-heating tests were conducted in the ROVERS (Radiation Orbital Vehicle Reentry Simulator) arc-jet facility of the AVCO System Division, Lowell, Massachusetts. This facility is described in detail in reference 4. An 11.5-cm-square nozzle was used for the tests. The simulated entry-heating tests of the ablator/ablator joint models were conducted in the supersonic arc-powered tunnel designated Apparatus A of the Langley entry structures facility. A nozzle with a 2.5-cm-diameter minimum and a 56-cm-diameter exit was used for the tests. Orbital cold-soak simulation tests were performed in a small cryogenic chamber using liquid nitrogen as the coolant.

Ablator/RSI joint model.- The simulated entry-heating tests of the ablator/RSI joint models were conducted in the supersonic arc-powered tunnel designated Apparatus B of the Langley entry structures facility. Apparatus B and the tunnel configuration used for the present tests are described in reference 5.

Test Environment

Ablator/ablator joint model.- The nominal test environments for the ablator/ablator models are shown in table I. A test stream of reconstituted air (23 percent by mass oxygen and 77 percent by mass nitrogen) was used in all tests. The heating-rate and pressure distributions over the models are shown in figures 3 and 4, respectively. The cold wall heating-rate data were obtained with small, thin circular foil calorimeters installed in a water-cooled calibration model which was the same size and shape as the test models. The pressure data were obtained with pressure transducers attached to small orifices located near the calorimeters. The measured pressure distribution agreed well with a modified Newtonian pressure distribution and the measured heating-rate distribution agreed well with the heating-rate distribution for a hemisphere cone. (See ref. 6.)

Ablator/RSI joint model.- The nominal test environment for the ablator/RSI joint models is shown in table II. Heating-rate and pressure distributions over the 12.7-cm-square test panel are shown in figures 5 and 6, respectively. The heating-rate data were obtained with a square thin-skin calorimeter. Pressure data were obtained with pressure transducers attached to small orifices in a square copper plate. Both the calorimeter and the copper plate were parts of calibration models of the same size and shape as the test models. All tests were conducted in air.

Test Procedures

Ablator/ablator joint model.- The ablator/ablator joint models were mounted on a water-cooled aluminum fixture (fig. 7) for testing in the simulated ascent- and entry-heating environments. These models were unrestrained during the cold-soak test.

Because of the large model size and limitations of the test section and model inserter, it was necessary to start the ascent- and entry-heating tests with the models in the test stream. The test procedure for the ascent tests was as follows: tunnel operating conditions were established prior to the test; a model was mounted in the tunnel and exposed to the test environment for a predetermined period of time; and, finally, the model was removed and posttest measurements and pictures were made. Previous tests in the ROVERS facility at similar conditions indicate that the stream environment was essentially unchanged over the test time. The test procedure for the cold-soak tests was as follows: the models were installed in the cryogenic chamber; liquid nitrogen was circulated in the chamber walls; the models were held at about 150 K for about 5 hours; finally,

the liquid nitrogen flow was stopped and the models were allowed to warm slowly to room temperature overnight in the chamber. The test procedure for the entry-heating tests was similar to the procedure for the ascent-heating tests except that the tests were terminated as soon as any thermocouple measured 368 K.

Ablator/RSI joint model.- The ablator/RSI joint models were mounted on a water-cooled wedge-shaped holder as shown by the schematic diagram in figure 8. Slots were cut in the phenolic-glass backup sheets to interrupt the lateral heat-conduction path. (See fig. 2.) The ends of the joints were sealed with a silicone-rubber resin to prevent gas flow into the joint from the side of the model. (See fig. 9.)

The test procedure for these tests was as follows: the tunnel operating conditions were established and the test environment allowed to stabilize; heating-rate and pressure measurements were made; the model was inserted into the test stream and exposed to the test environment until a temperature rise of 167 K was obtained at any thermocouple location; the model was then removed from the stream and posttest measurements of heating rate and pressure were made. The measurements showed that the test conditions did not change significantly during the tests.

RESULTS AND DISCUSSION

Two models, each with a different seal, of an ablator/ablator joint design and an ablator/RSI joint design were tested in simulated shuttle-orbiter environments. The ablator/ablator joint models were sequentially subjected to ascent heating, orbital cold soak, and entry heating. The ablator/RSI joint models were subjected to entry heating only. The thermal performance of the joints was evaluated by posttest appearance, material recession, and back-surface temperature response, and by comparisons with previous test data of similar models without joints.

Ablator/Ablator Joint Models

Ascent-heating and cold-soak tests.- Back-surface temperature histories for joint models with a silicone-foam seal and a silica-felt seal are shown in figures 10 and 11, respectively. The temperature histories, up to 560 seconds, show a uniform back-surface temperature rise of approximately 20 K for both models. Peak recorded temperatures (caused by heat soak) were approximately 340 K to 350 K.

In table III, temperature data from these models are compared with similar data for a model without a joint. (See ref. 2.) The jointless model was made of the same ablation material used in the present study. The data in table III and in figures 10 and 11 indicate the seals had no adverse effect on the thermal performance during the ascent-heating tests.

Figures 12 and 13 show models after the cold-soak test. Since the cold soak had no visible effects on the models, the effects of the ascent heating can be described with the help of these preentry heating photographs. The silicone foam had a tendency to swell and protrude above the ablator, and some cracks appeared in the stagnation region during ascent heating (fig. 12). Also, a slight recession of the seal occurred at about 45° from the stagnation line. (See fig. 12.)

The silica-felt seal lost resiliency near the surface, cracked in the stagnation region, and had a tendency to separate from the ablator. (See fig. 13.) No evidence was found, either by temperature measurements or by appearance, of gas flow into the permeable silica felt. This lack of such gas flow was probably the result of the very low stagnation pressure in the ascent tests.

Entry-heating test. - Back-surface temperature histories for the silicone-foam seal model and silica-felt seal model are shown in figure 14. Posttest photographs of each model are shown in figures 15 and 16. A section of the silicone-foam seal about 5 cm long and 0.6 cm deep was removed. (See fig. 15.) (About 10 percent or less of this lost material was removed during the ascent test.) The deterioration of the seal resulted in a rapid temperature rise at T/C 4. (See fig. 14(a).) The cause for the early, rapid response of T/C 3 is not known. It may have been the result of a small hot gas leak between the model and the water-cooled side plate of the model holder - a problem experienced in previous tests of jointless models.

The silica-felt material melted and flowed along the joint on the cylindrical portion of the model during the test. (See fig. 16(a).) The ablation of the silica-felt seal caused a significantly increased recession of the surrounding charring ablation material. (See fig. 16(b).)

The early and rapid temperature rise shown by T/C 4 (fig. 14(b)) may indicate that some hot boundary-layer gas inflow occurred on the cylindrical portion of the model because of the permeability and/or cracking of the silica felt, the pressure level, and the pressure gradient. However, T/C 2, on the other side of the model and 5° closer to the stagnation line, did not show the rapid increase in temperature. The early temperature rise at T/C 6 (fig. 14(b)) was probably the result of inflow of hot gas; the inflow was caused by the reattachment of flow separated by surface roughness upstream of T/C 6. The asymmetry in temperature rise may have been caused by differences in the packing density of the silica felt or a local burn-through in the felt. (Note cracks in the silica felt in fig. 16(a).)

Temperature and recession data for the joint models and for a similar jointless model for the entry-heating tests are shown in table IV. The data show the joints were very detrimental to the performance during the entry-heating tests. The silica-felt seal

receded about twice as much in the stagnation region as did the silicone-foam seal or the jointless model.

Ablator/RSI Joint Models

Back-surface temperature histories for the entry-heating simulation tests are shown in figure 17. Photographs of both models before and after testing are shown in figures 18 and 19. The silicone-rubber seal expanded out of the joint and the subsequent effect on the local flow is evident in figures 18(b) and 18(c). Significant downstream deposition of ablation products on the RSI surface occurred. A large section of the seal in the upstream corner portion of the joint was burned away. This local failure may have been caused by the high heat flux in this area (fig. 5) and explains the early and rapid temperature rise at T/C 1 and T/C 7. (See fig. 17(a).)

The silica-felt seal did not expand out of the joint. However, the model failure in the upstream corner of the joint (figs. 19(b) and 19(c)) was similar to the failure shown by the silicone-rubber seal model. Again, this seal failure may have resulted from the high heating rate in this area and it explains the early and rapid temperature rise at T/C 7. (See fig. 17(b).) Although there is some deposition of ablation products on the RSI coating (figs. 19(b) and 19(c)), the amount of deposition is significantly less with the silica-felt seal than with the silicone-rubber seal.

No attempt was made to evaluate quantitatively the extent of deposition or the effects of the deposition on the RSI surface. However, the extensive deposition seen in figure 18 may have deleterious effects on both the thermal and mechanical performance of the RSI coating. Therefore, further evaluation of these effects is needed for future design work.

Neither joint seal material performed satisfactorily. The silica-felt seal appeared the better of the two seal materials from the point of view that it expanded less, produced less downstream deposition of ablation products, and did not disturb the local flow field significantly. However, the silicone-rubber seal showed much better insulative qualities in that the model back-surface temperature rise was much slower. The test time for the prescribed back-surface temperature rise was more than three times longer with the silicone-rubber seal.

CONCLUDING REMARKS

Two types of ablative leading-edge joints for a space-shuttle orbiter have been evaluated in simulated heating environments. One type was designed for the chordwise joint between segments of an ablative leading edge. Models of this type of joint were sequentially tested in simulated ascent-heating, orbital cold-soak, and entry-heating environments. The other type was designed for the spanwise joint between ablative

leading-edge segments and the RSI tiles. Models of this type of joint were tested in a simulated entry-heating environment only.

Both joint designs were essentially butt joints (5° bevel) with a flexible seal material in the joint. Two types of seals were used for each joint design. A silica-felt seal and a silicone-foam seal were used with the chordwise joint. A silica-felt seal and a wavy silicone-rubber seal were used with the spanwise joints.

The models with chordwise joints performed as well as similar models without joints in the ascent-heating tests. However, in the entry-heating tests, the model with the silicone-foam seal had a local failure of the seal. The model with the silica-felt seal experienced high recession along the joint in the stagnation region. The back-surface temperatures of both models rose much more rapidly than corresponding temperatures on a similar jointless model.

Both models of the spanwise joint had local failures of the joints during the entry-heating tests. The wavy silicone-rubber seal expanded above the surrounding material, interfered with the flow over the model, and significantly increased the mass of ablation products deposited downstream on the reusable surface insulation (RSI) panel.

~~In general, additional work is required on seals for both spanwise and chordwise-~~
joint designs. In particular, the effect of the seal materials on local flow and downstream deposition must be carefully evaluated. Deposition of ablation products on downstream RSI tiles was observed in these tests. This deposition may have deleterious effects on both the thermal and mechanical performance of the RSI tiles.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., May 16, 1975.

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TABLE I.- TEST ENVIRONMENTS FOR CHORDWISE-JOINT MODELS

Ascent heating:

q_{cw} , kW/m ²	100
H_{∞} , MJ/kg	24
$p_{t,2}$, atm	0.0007
Time, s	560
Test stream	Reconstituted air

Cold soak:

5 hours	Between 144 K to 158 K
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Entry heating:

q_{cw} , kW/m ²	850
H_{∞} , MJ/kg	9.9
$p_{t,2}$, atm	0.063
Test stream	Reconstituted air

TABLE II.- ENTRY-HEATING SIMULATION TEST ENVIRONMENT
FOR SPANWISE-JOINT MODELS

$(q_{cw})_{mp}$, kW/m ²	310
H_{∞} , MJ/kg	7.2
p_{mp} , atm	0.042
Angle of attack, deg	32
R_{∞} , cm ⁻¹	652
Test stream	Air

TABLE III.- COMPARISON OF SIMULATED ASCENT-HEATING TEST DATA FOR
ABLATOR/ABLATOR JOINT MODEL AND MODEL WITHOUT JOINT

	Without joint	Silica-felt seal	Silicone-foam seal
Test time, s	560	560	560
ΔT_2 at end of test, K	33	18	23
ΔT_2 maximum, K	72	51	61

TABLE IV.- COMPARISON OF SIMULATED ENTRY-HEATING TEST DATA FOR
ABLATOR/ABLATOR JOINT MODEL AND MODEL WITHOUT JOINT

	Without joint	Silica-felt seal	Silicone-foam seal
Test time, s	258	98	72
ΔT_4 at end of test, K	20	83	75
ΔT_2 at end of test, K	75	27	22
ΔT_2 maximum, K	121	31	23
Recession in stagnation region, cm	0.22	0.55	0.23

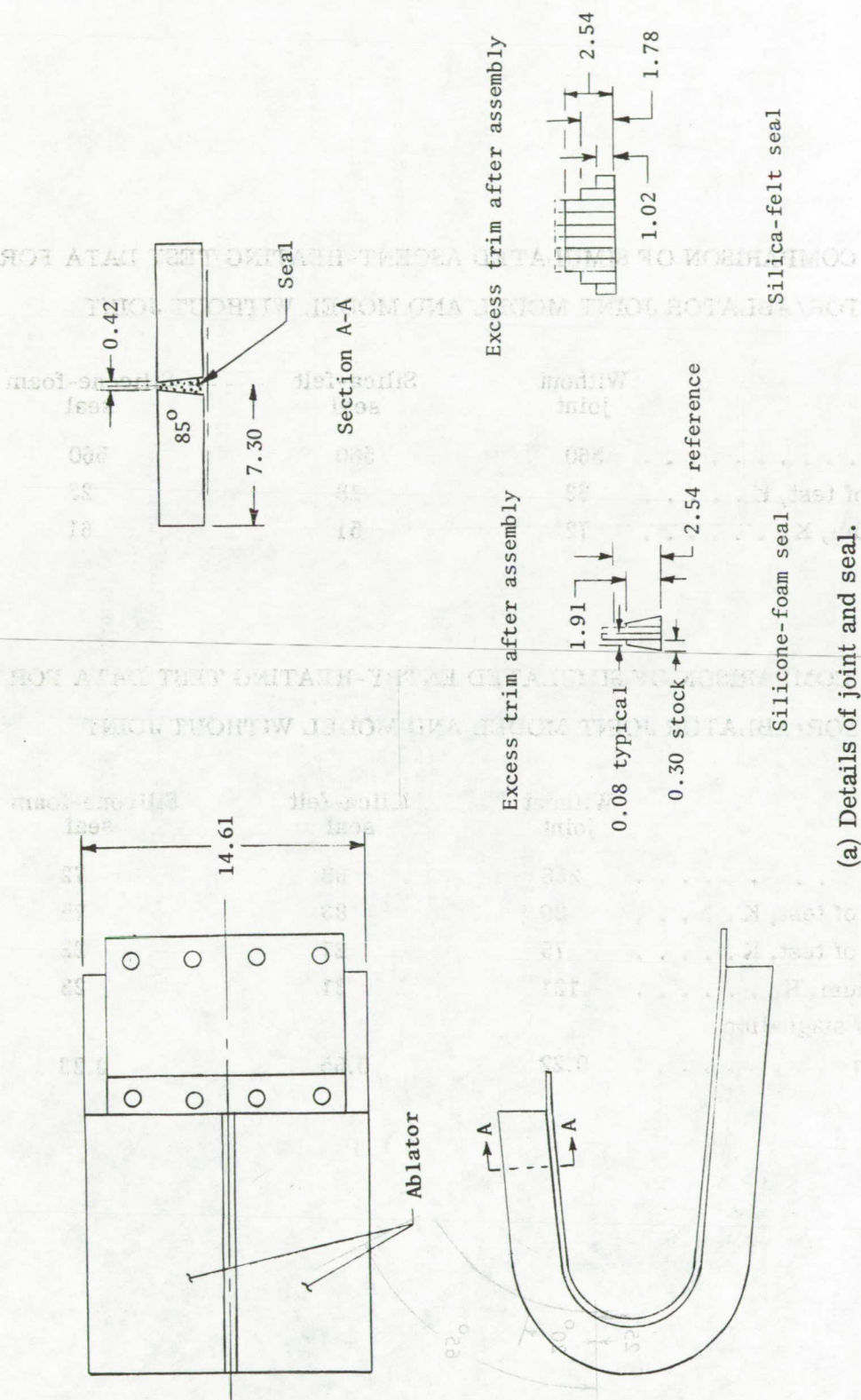
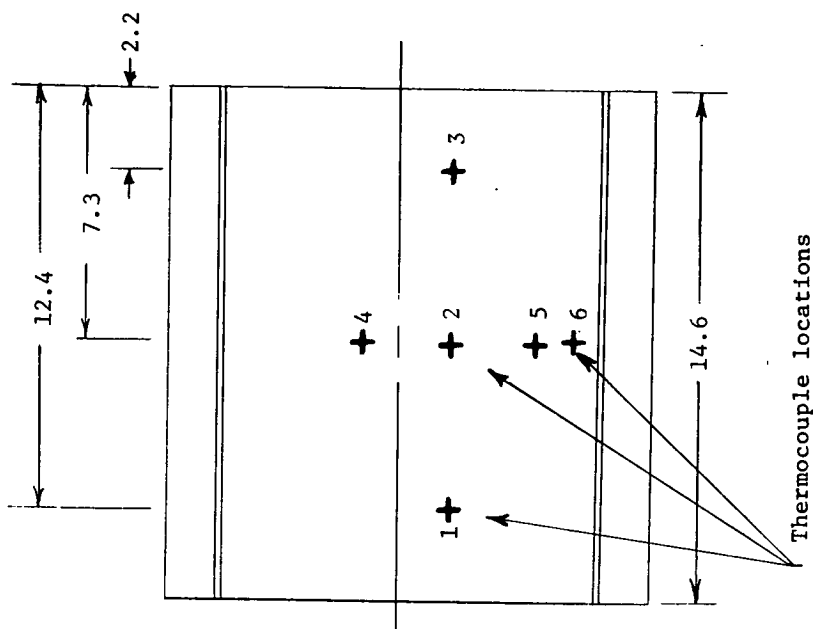
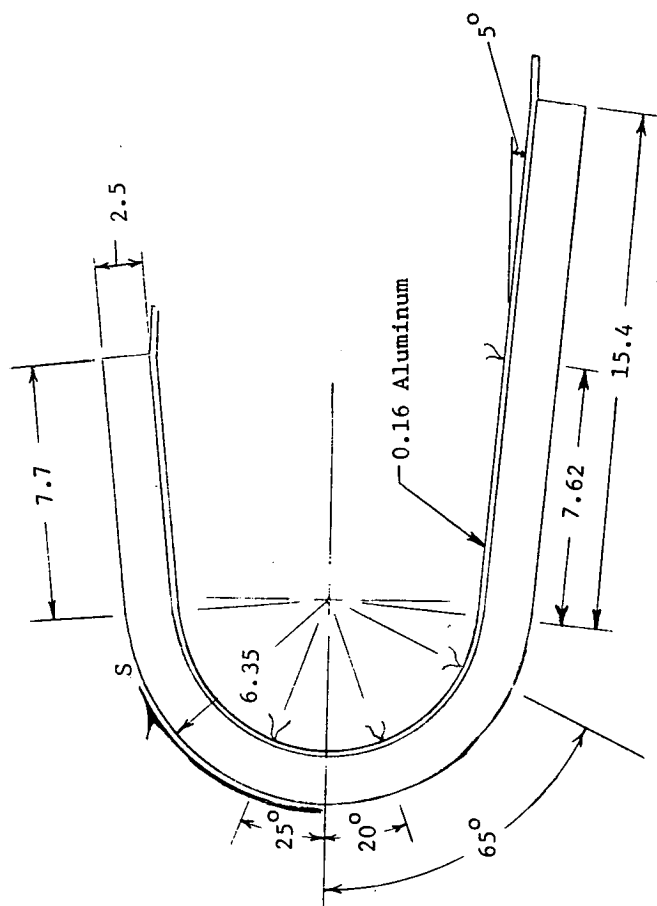


Figure 1.- Chordwise ablator/ablator joint model (dimensions in centimeters).



(b) Overall model geometry and instrumentation.

Figure 1.- Concluded.

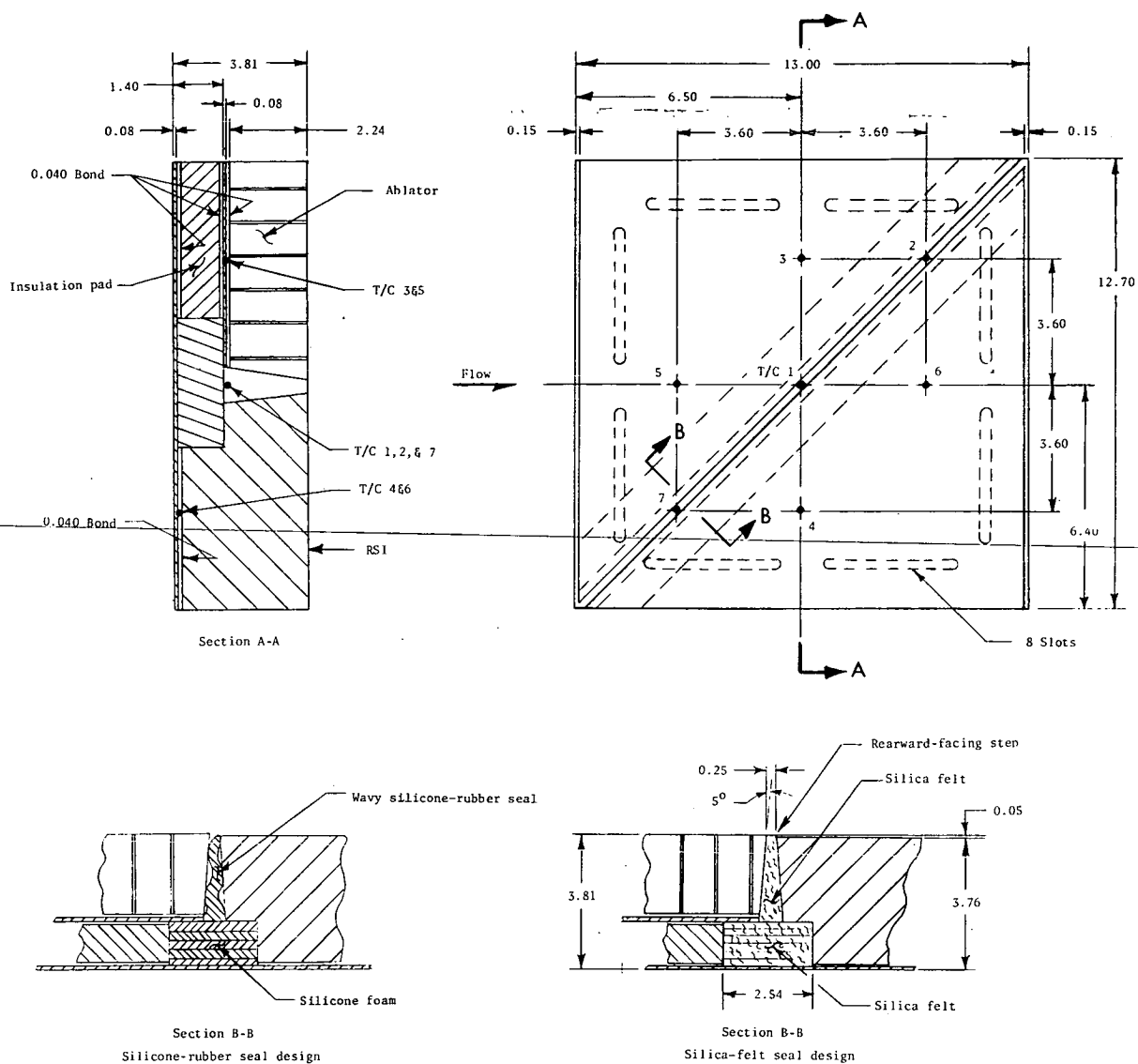


Figure 2.- Spanwise ablator/RSI joint models (dimensions in centimeters).

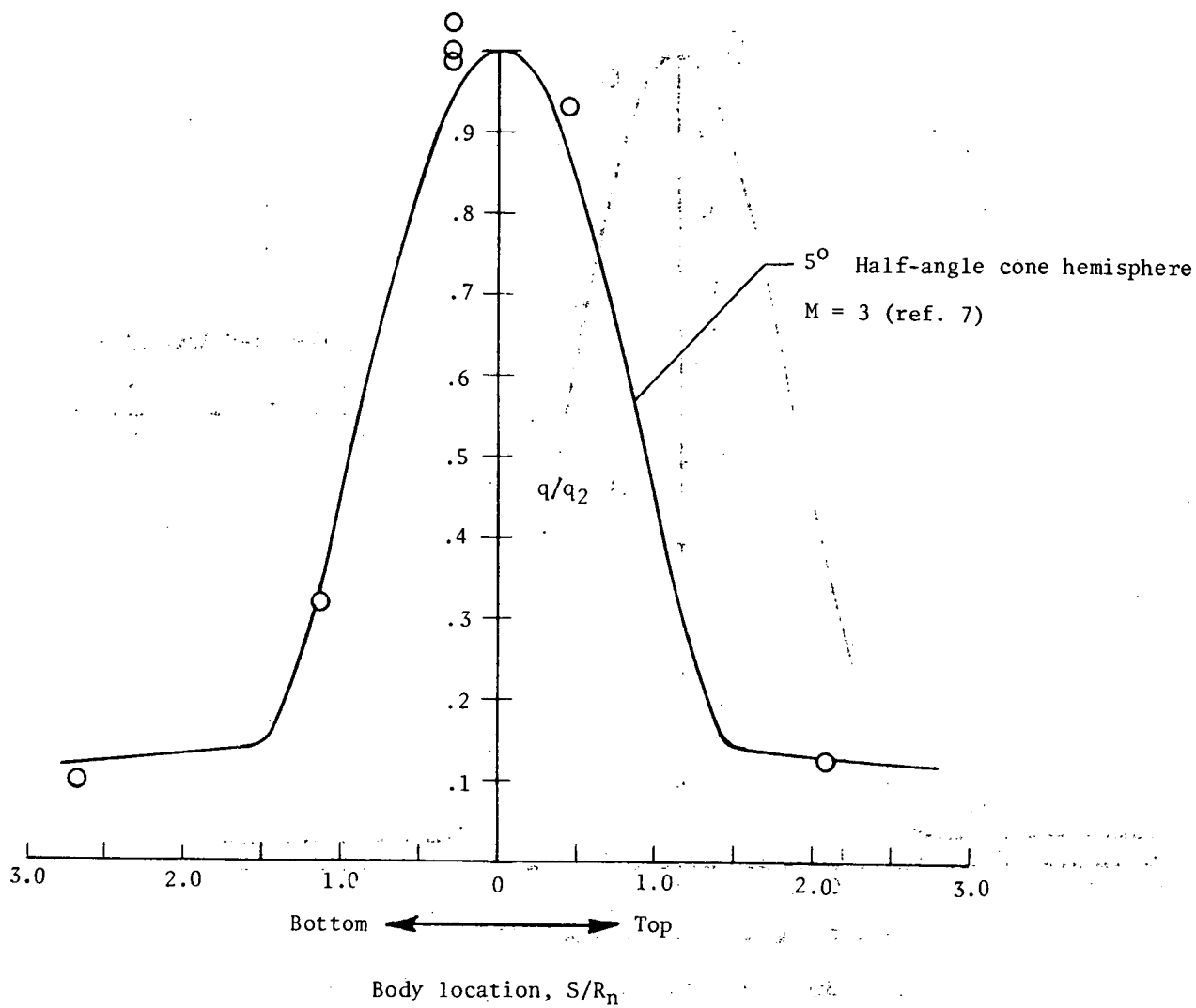


Figure 3.- Heating-rate distributions on ablator/ablator joint model test.

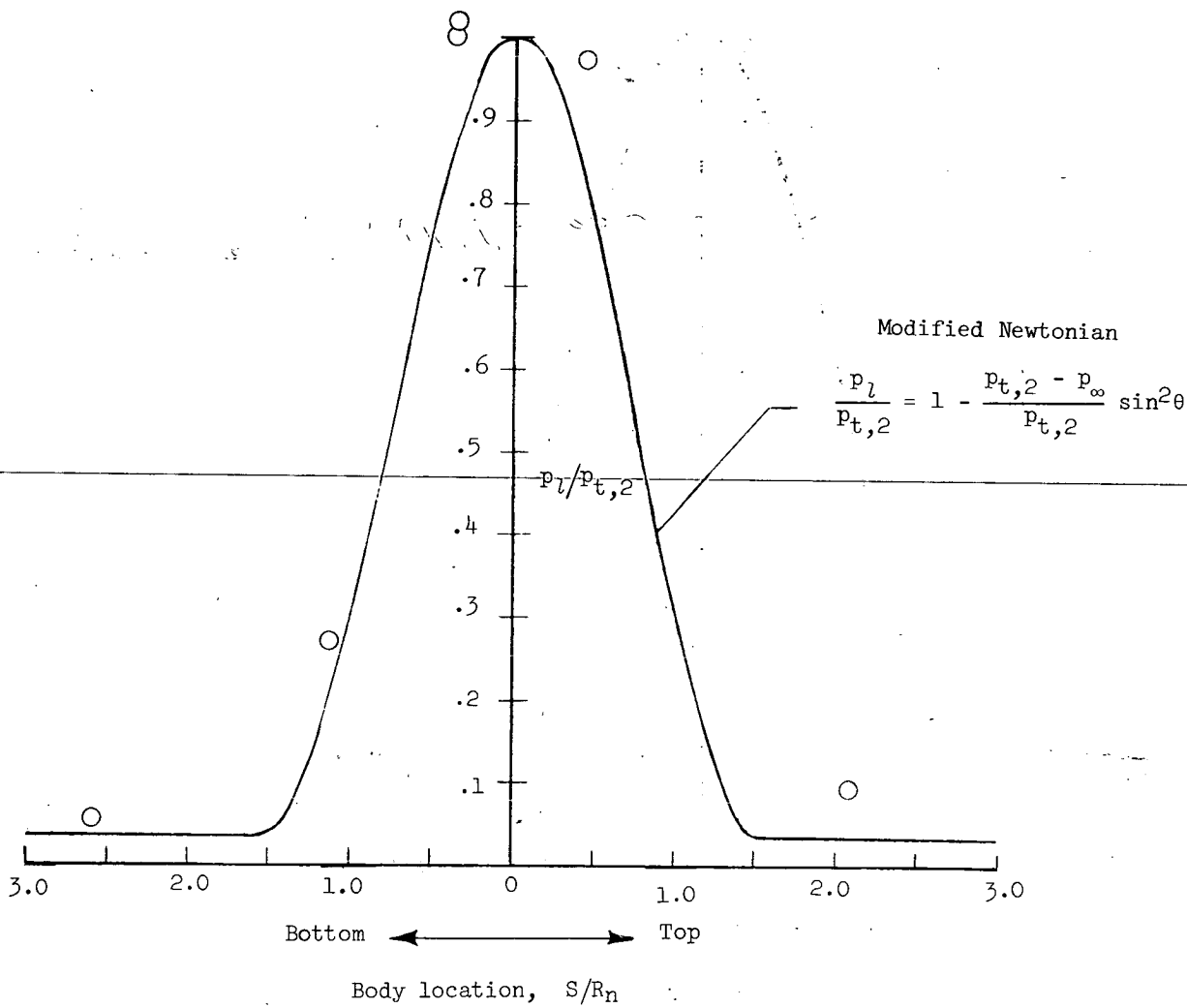


Figure 4.- Pressure distributions for ablator/ablator joint model test.

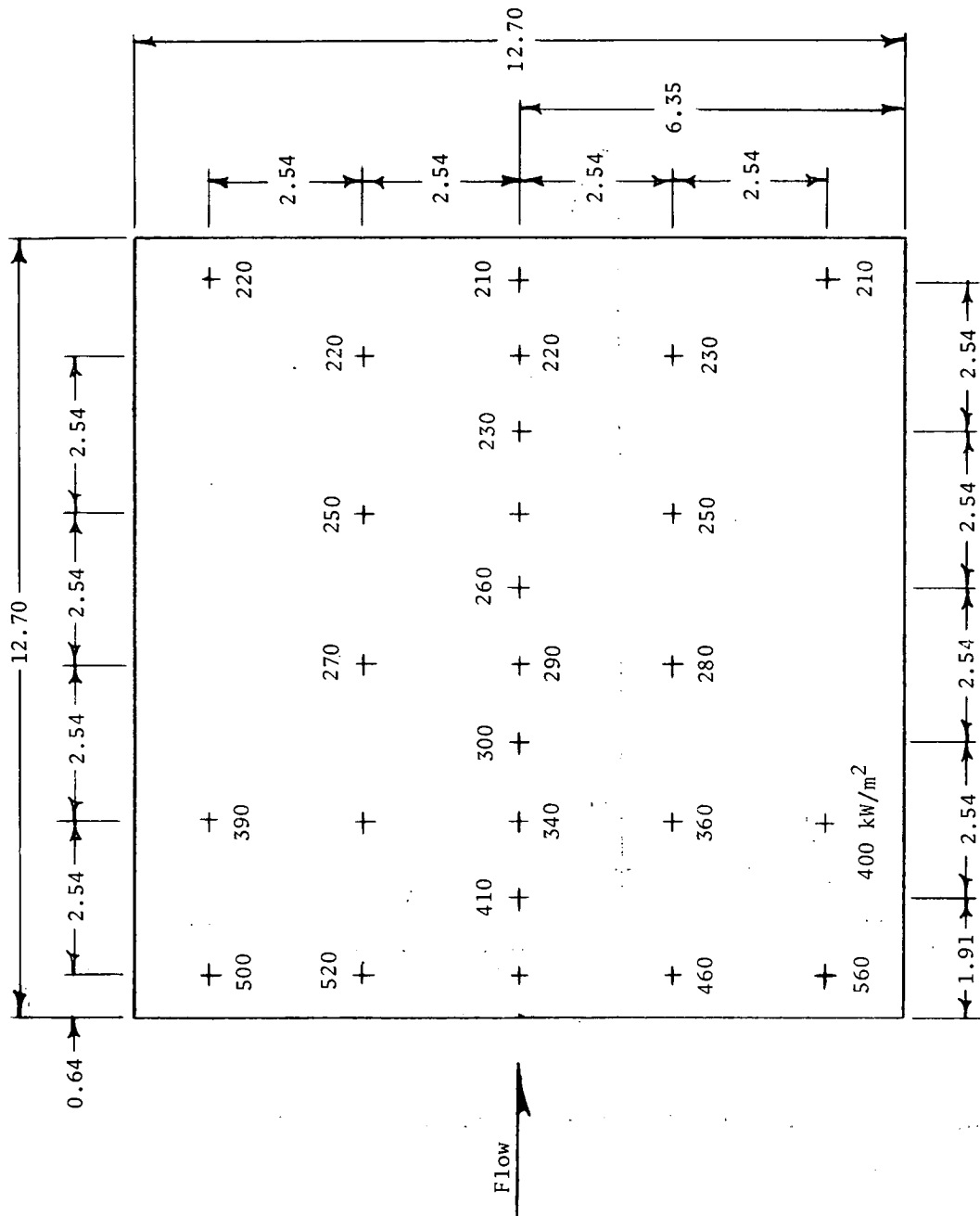


Figure 5.- Heating-rate distributions measured on ablator/RSI joint model calorimeter (dimensions in centimeters).

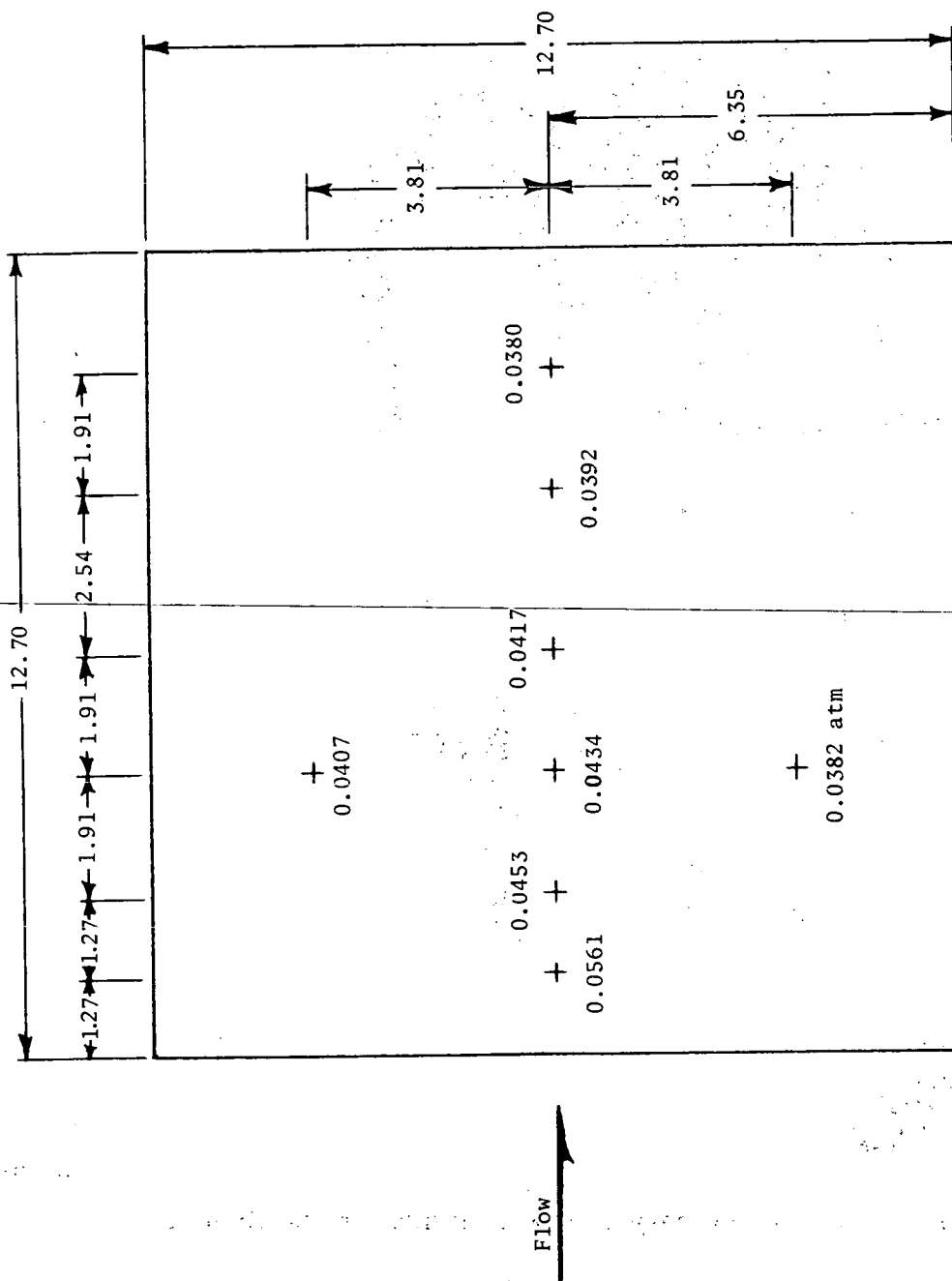
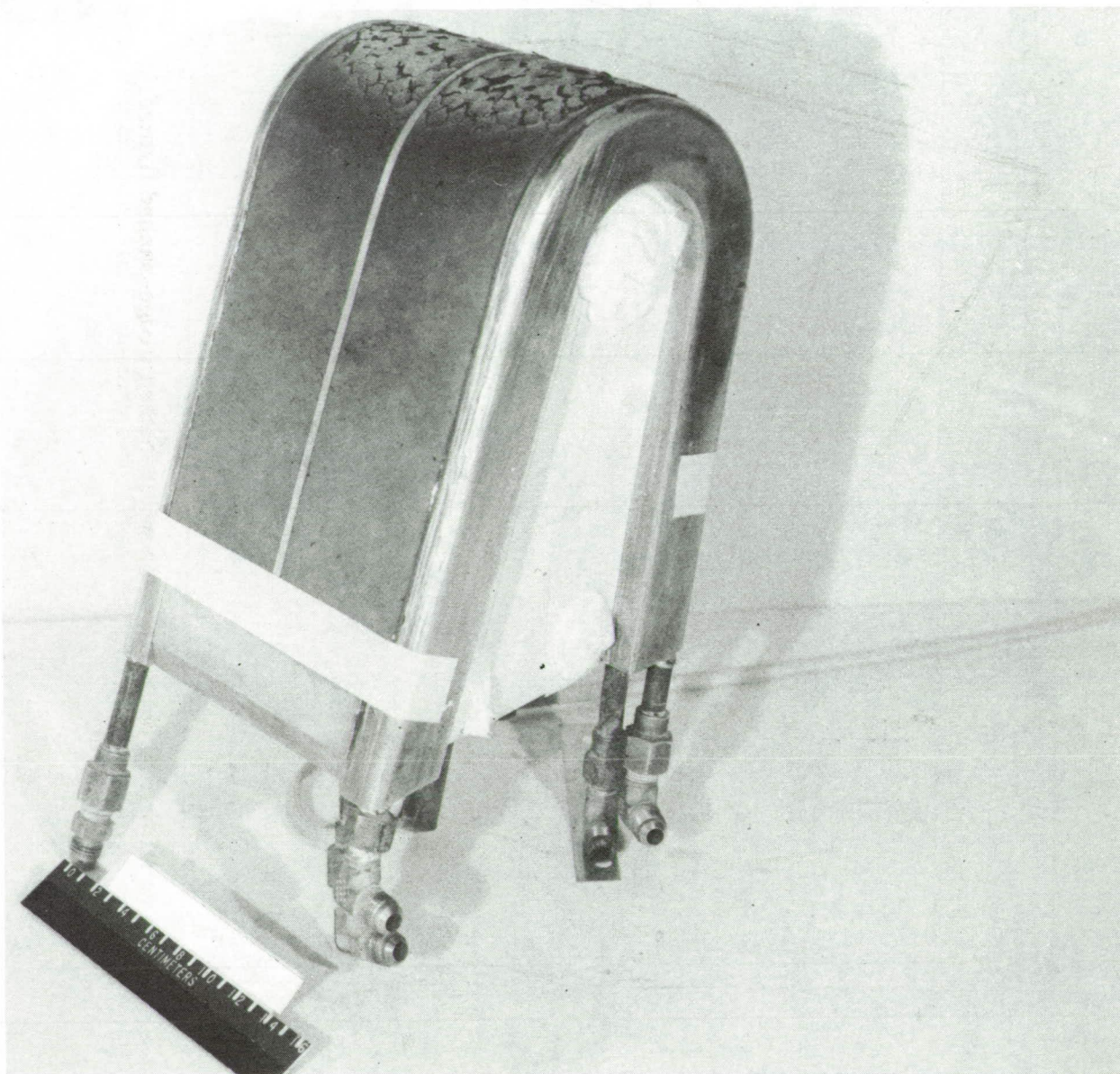


Figure 6.- Pressure distributions measured on ablator/RSI joint model pressure plate (dimensions in centimeters).



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Figure 7.- Chordwise-joint model mounted on test fixture.

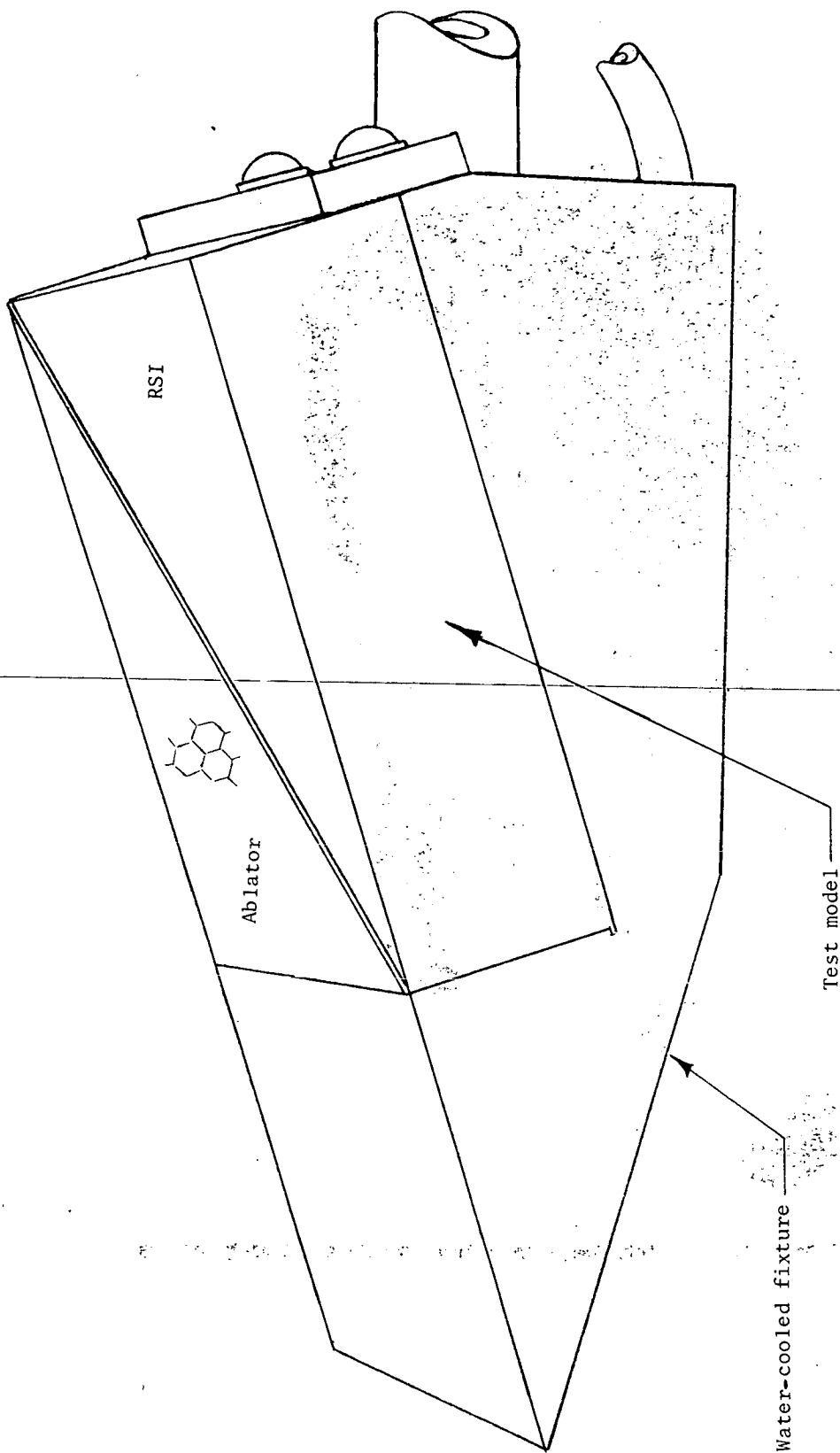
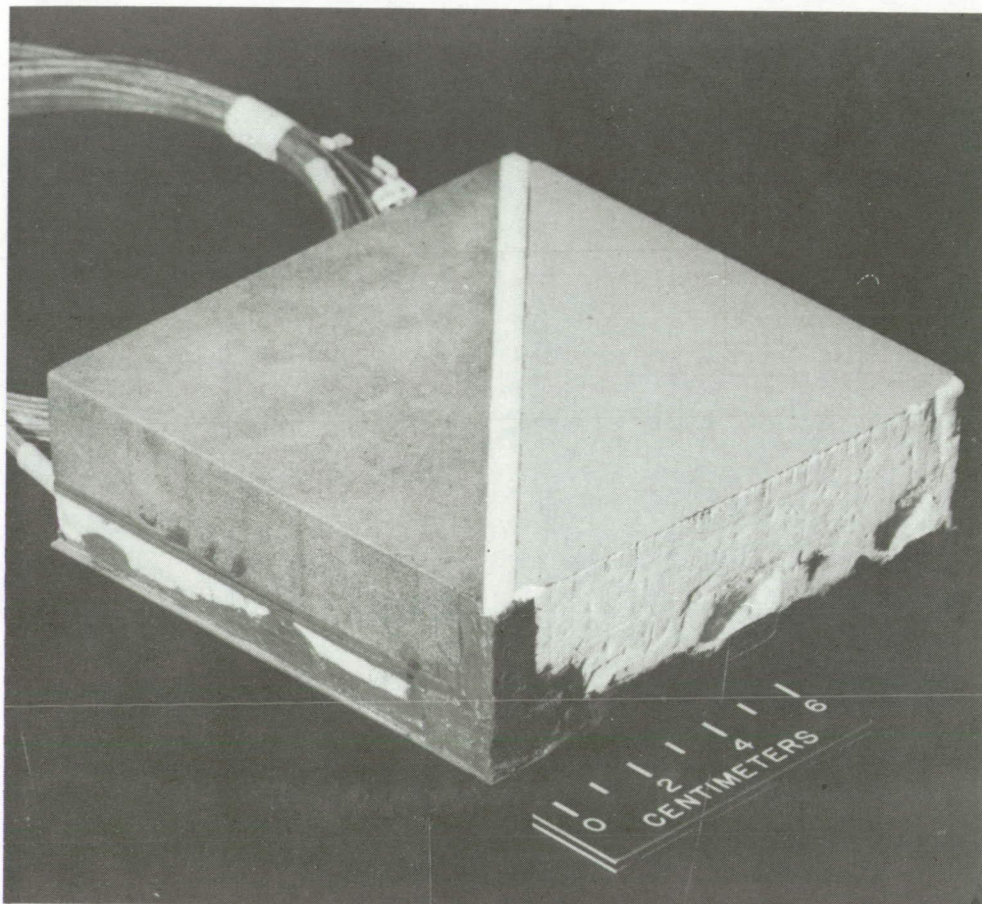


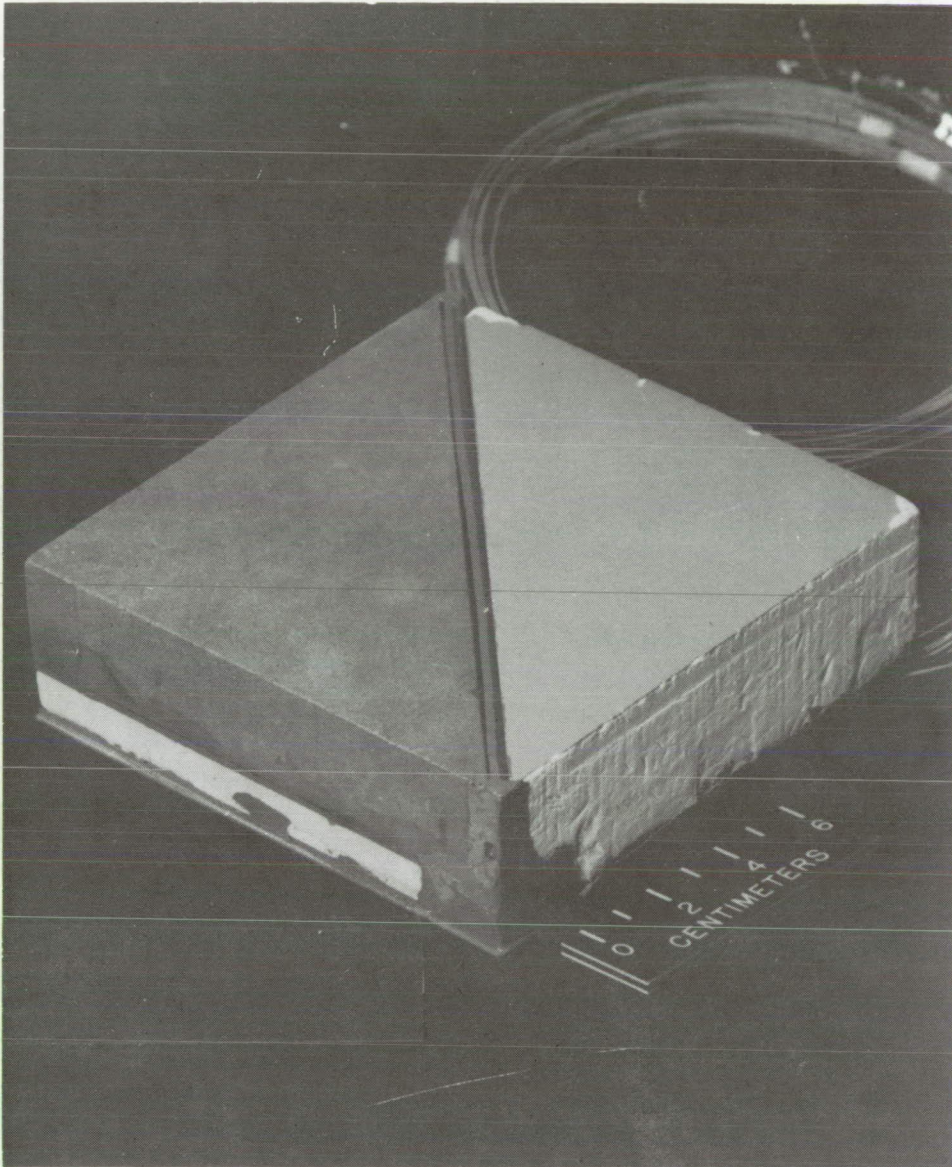
Figure 8.- Square panel test model mounted on water-cooled wedge-shaped fixture.



(a) Silica-felt seal.

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Figure 9.- Untested ablator/RSI joint models.



(b) Silicone-rubber seal.

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Figure 9.- Concluded.

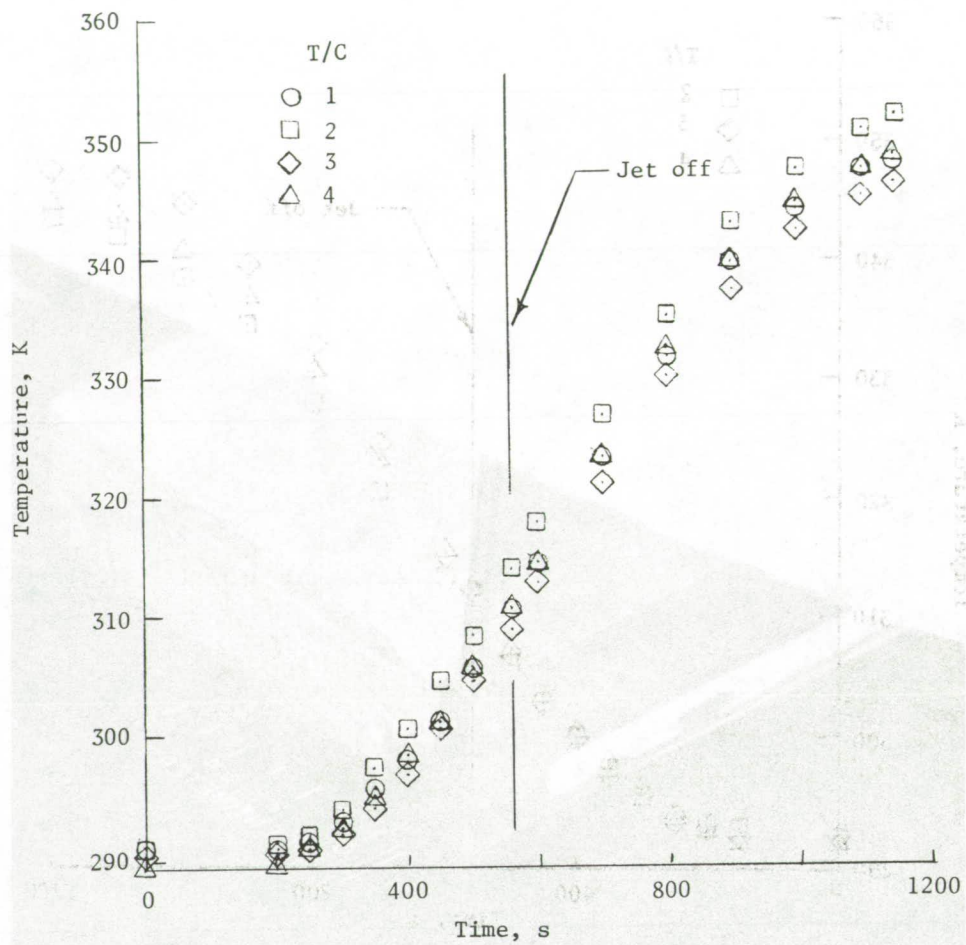


Figure 10.- Back-surface temperature histories for the ablator/ablator silicone-foam seal model during ascent-heating test.

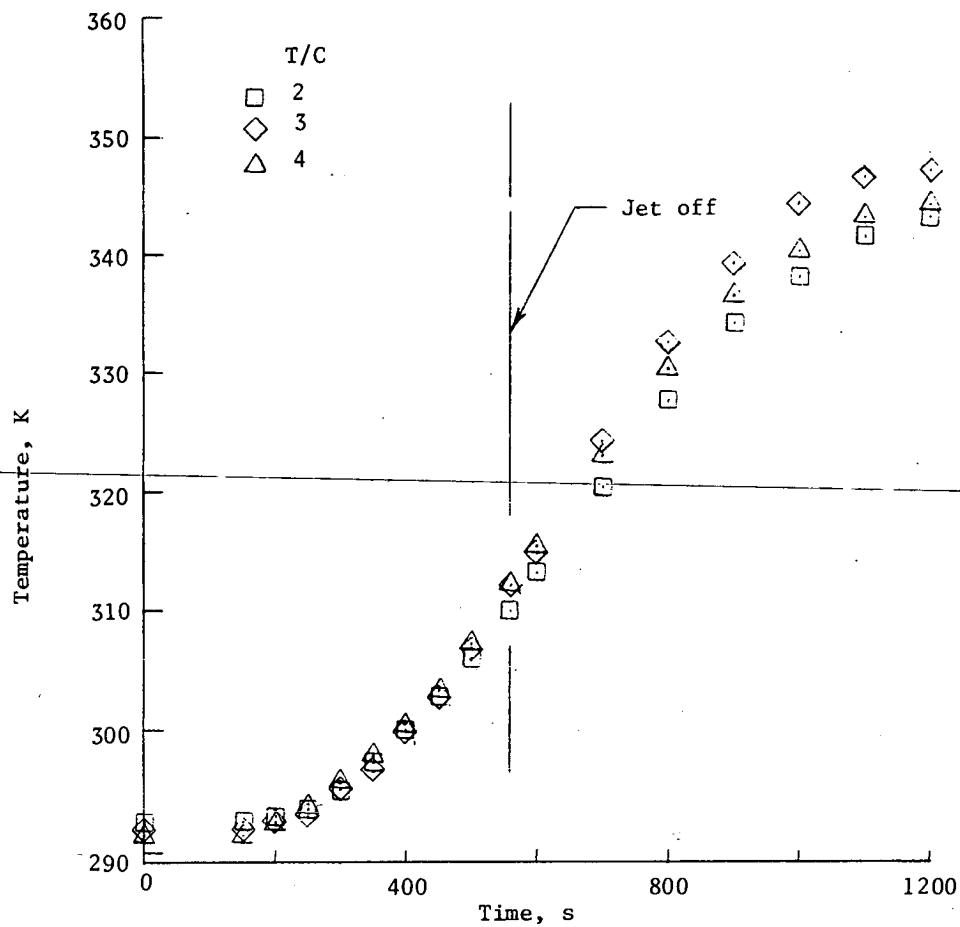
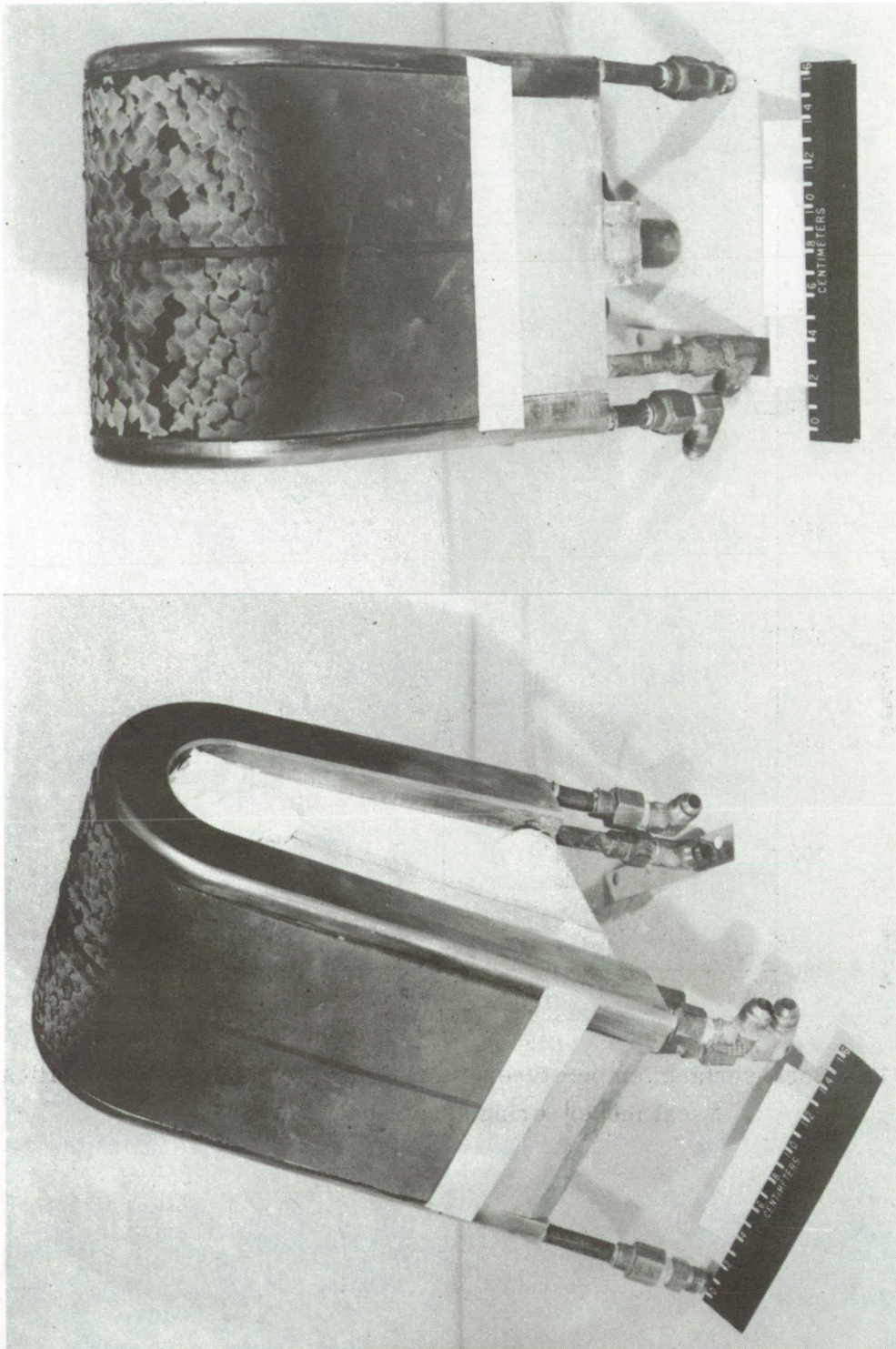
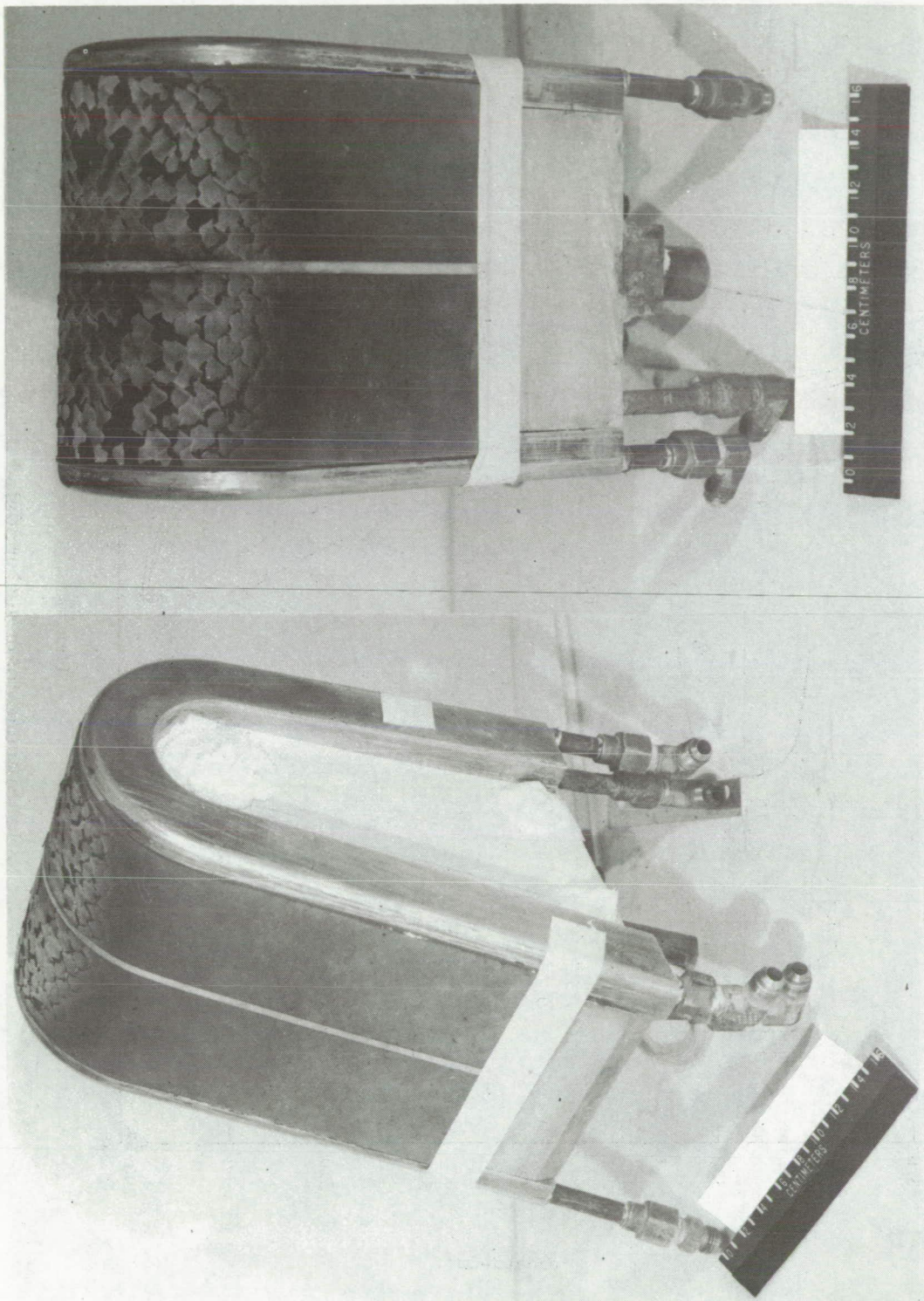


Figure 11.- Back-surface temperature histories for the ablator/ablator silica-felt seal model during ascent-heating test.

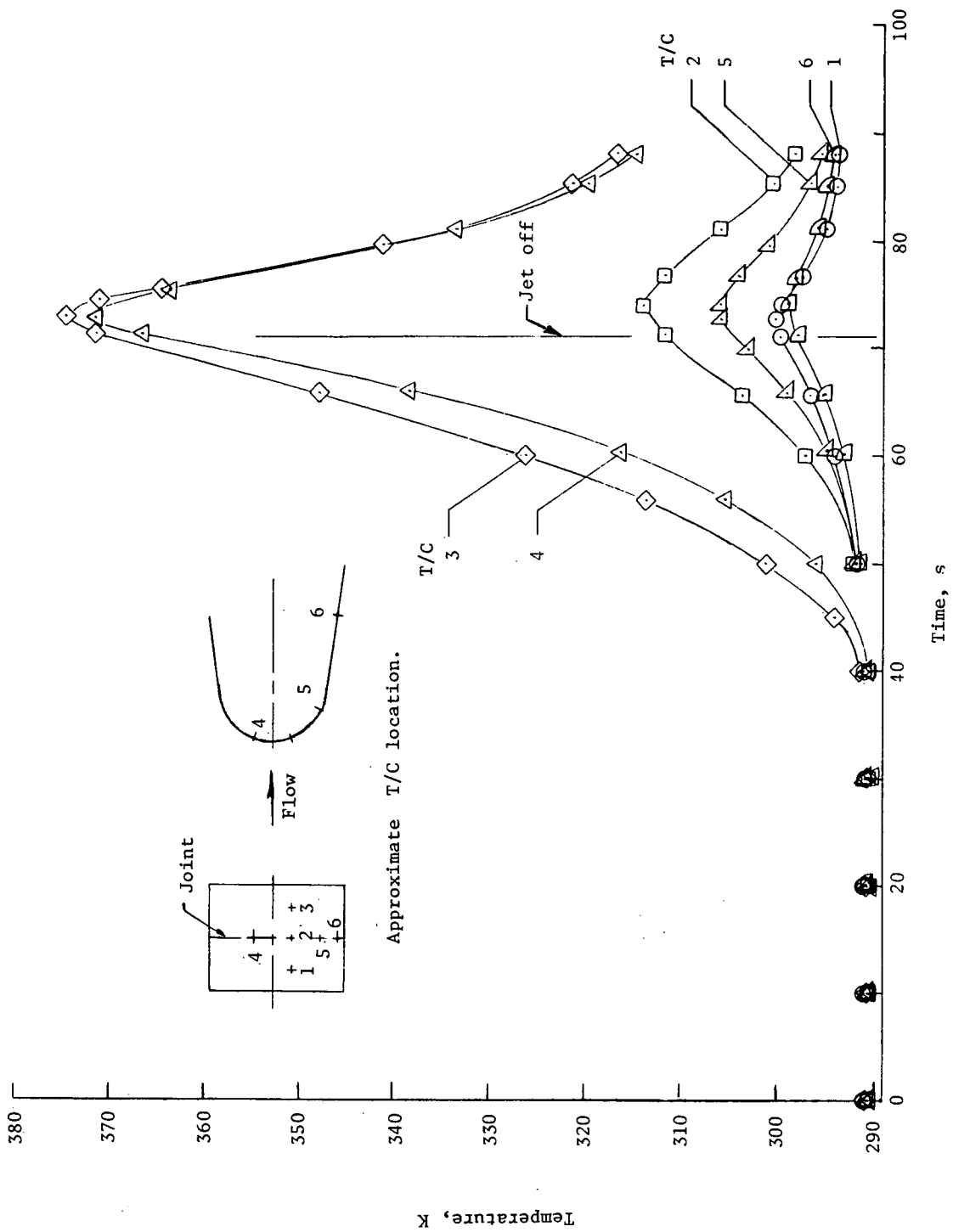


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Figure 12.- Silicone-foam seal joint model prior to simulated entry-heating test.



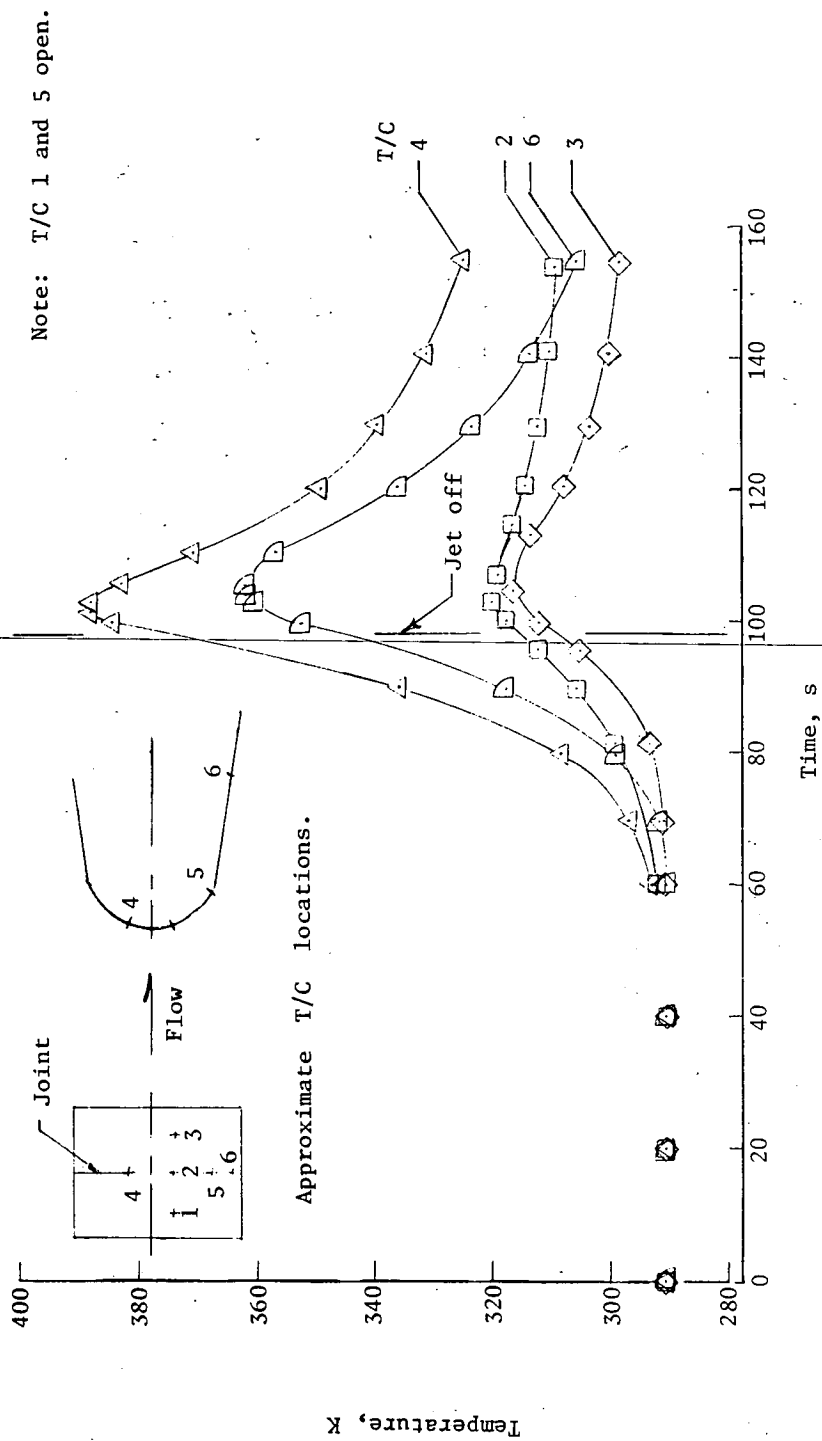
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Figure 13.- Silica-felt seal joint model prior to simulated entry-heating test.



(a) Silicone-foam seal model.

Figure 14.- Back-surface temperature histories of chordwise-joint model.



(b) Silica-felt seal model.

Figure 14.- Concluded.

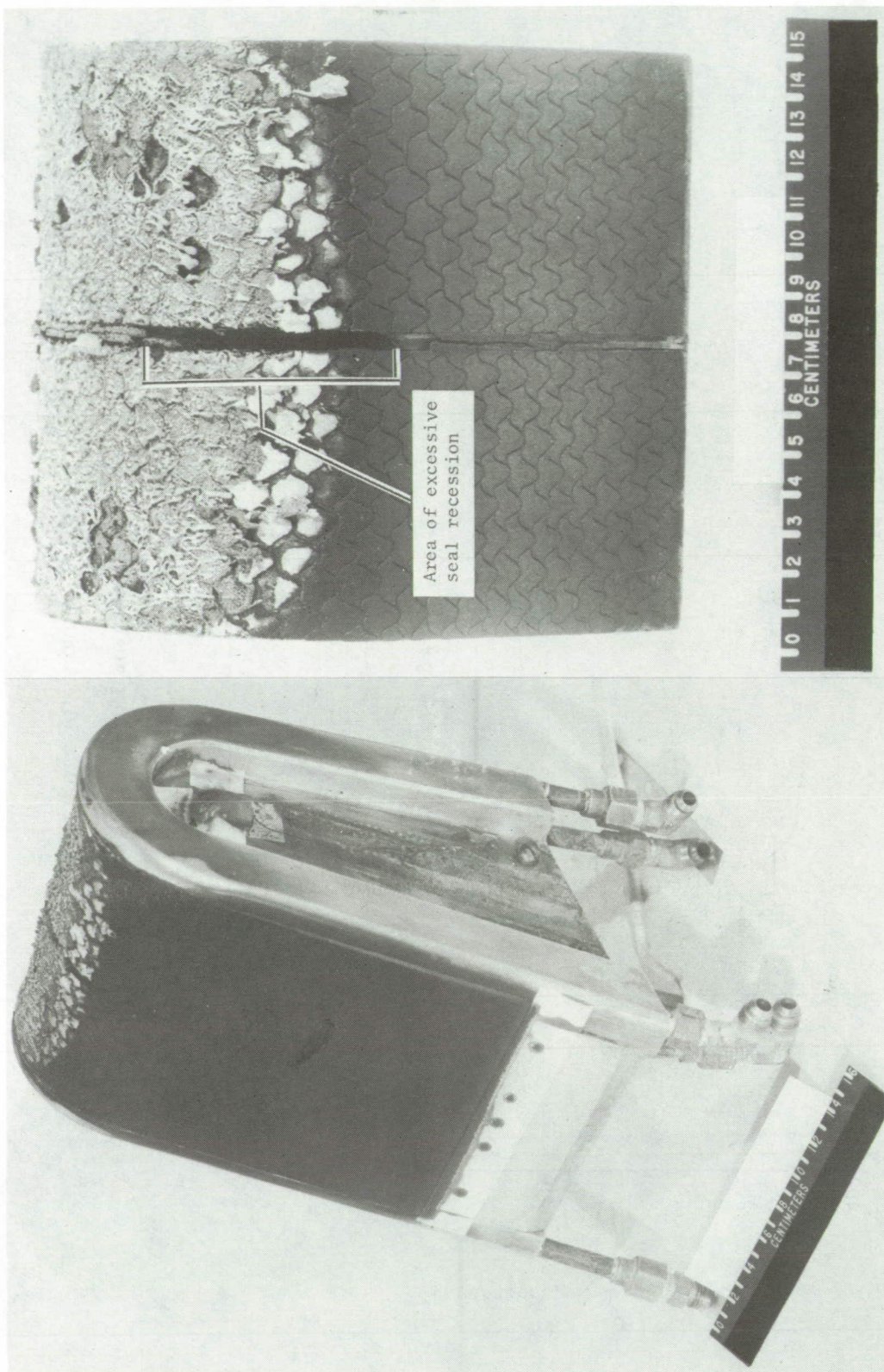
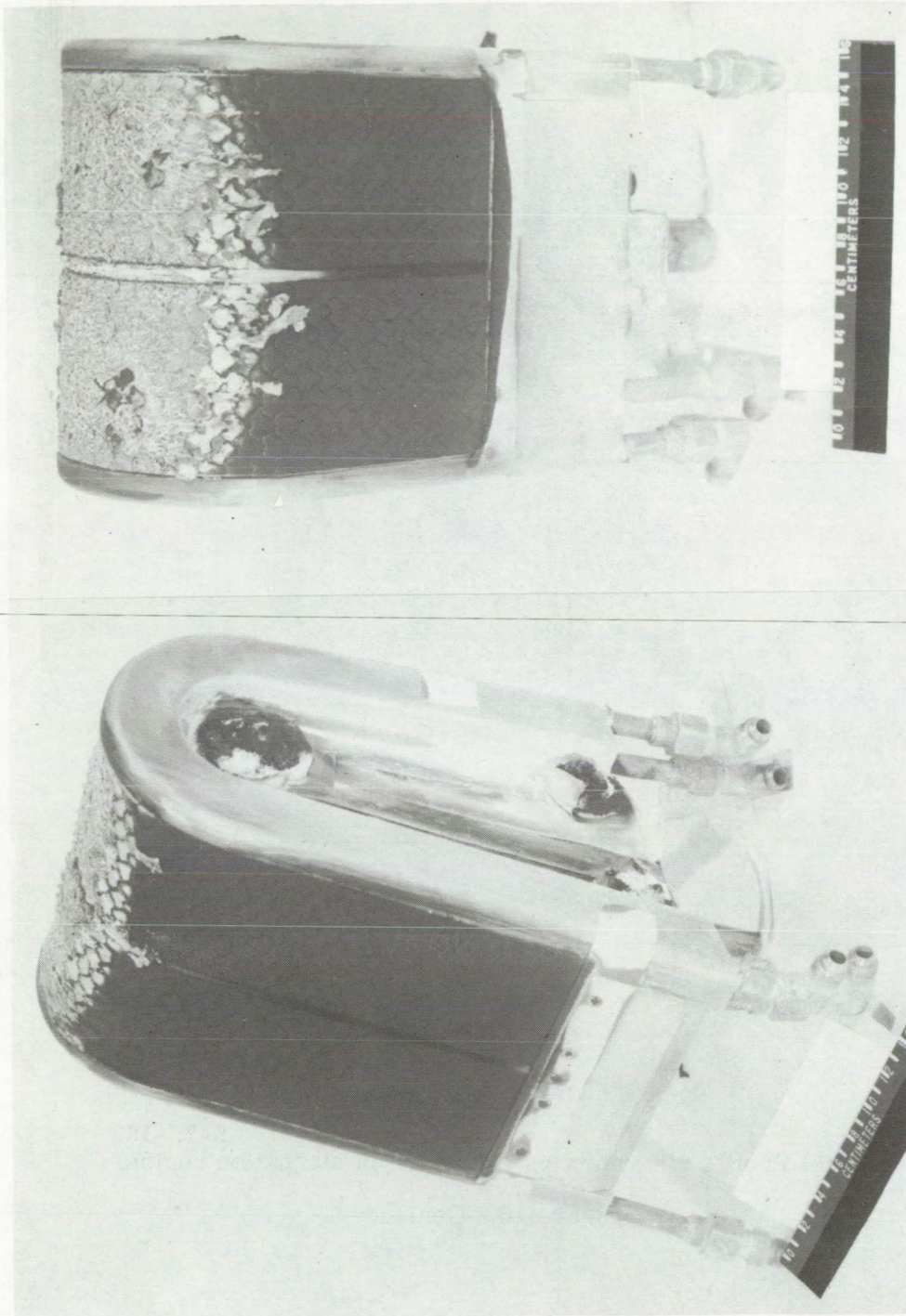
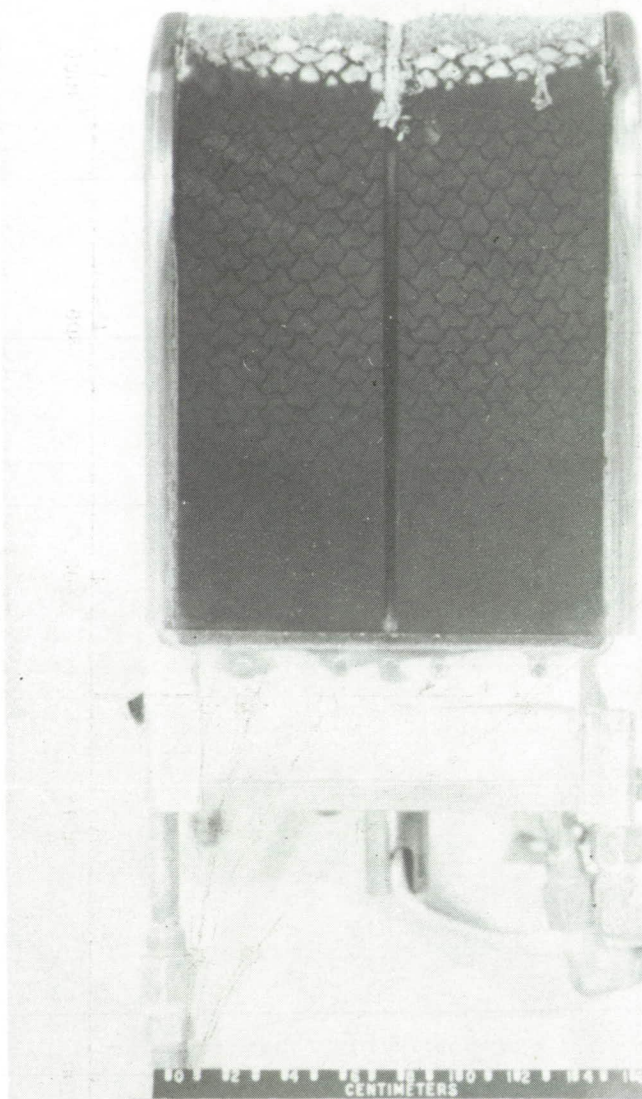


Figure 15.- Ablator/ablator silicone-foam seal model after simulated entry-heating test. L-75-160



(a) Isometric and oblique views showing general features. L-75-161

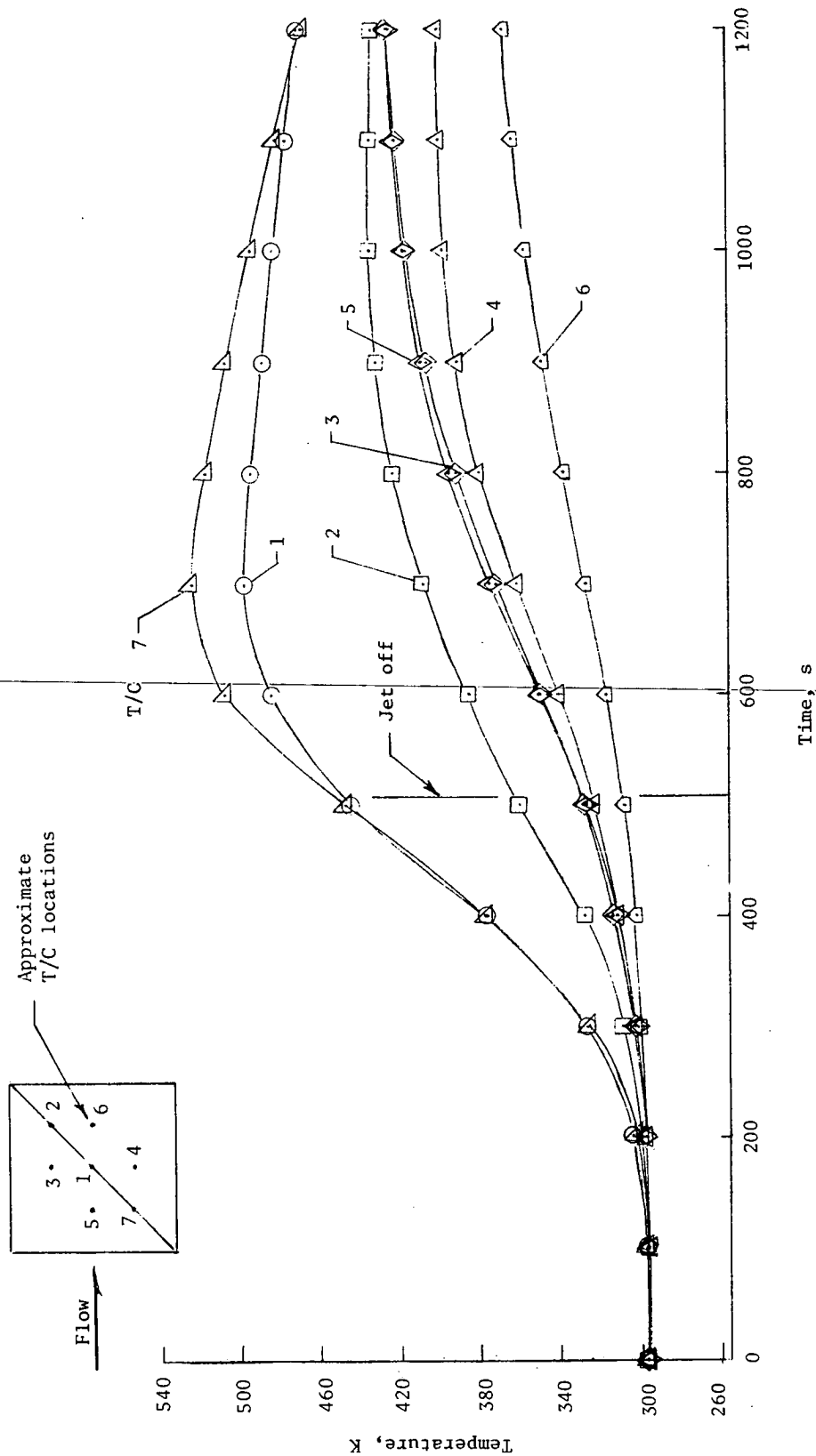
Figure 16.- Ablator/ablator silica-felt seal model after simulated entry-heating test.



L-75-162

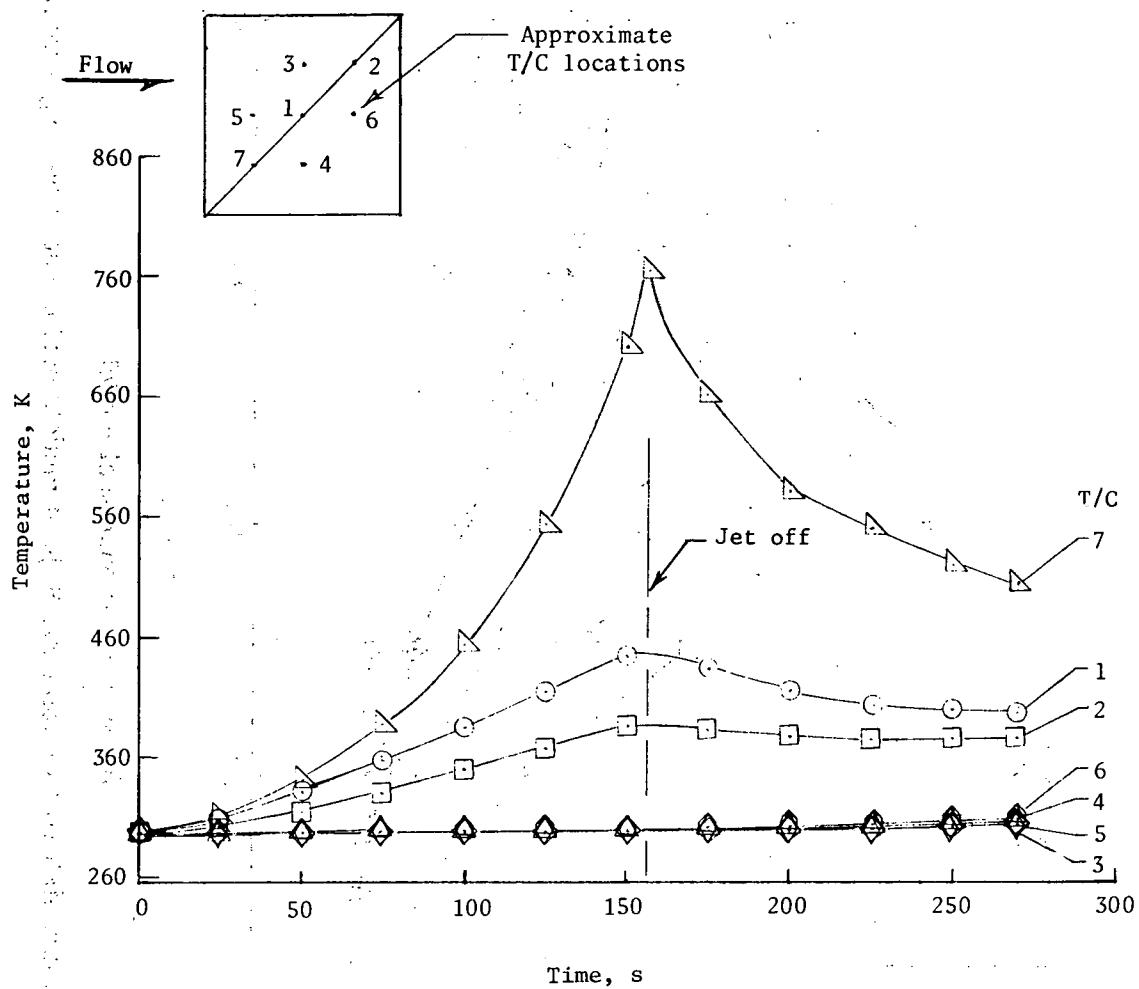
(b) Profile view showing recession in stagnation region.

Figure 16.- Concluded.



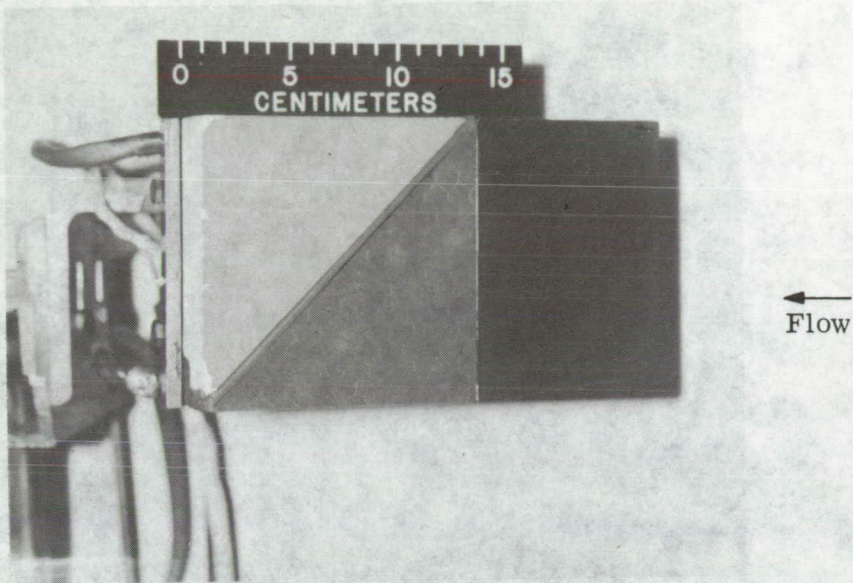
(a) Silicone-rubber seal model.

Figure 17.- Temperature histories of ablators/RSI joint models during entry-heating simulation test.

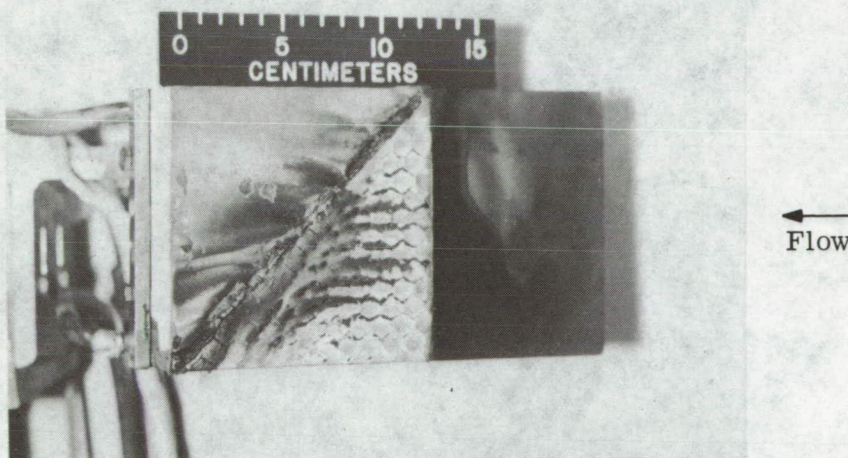


(b) Silica-felt seal model.

Figure 17.- Concluded.

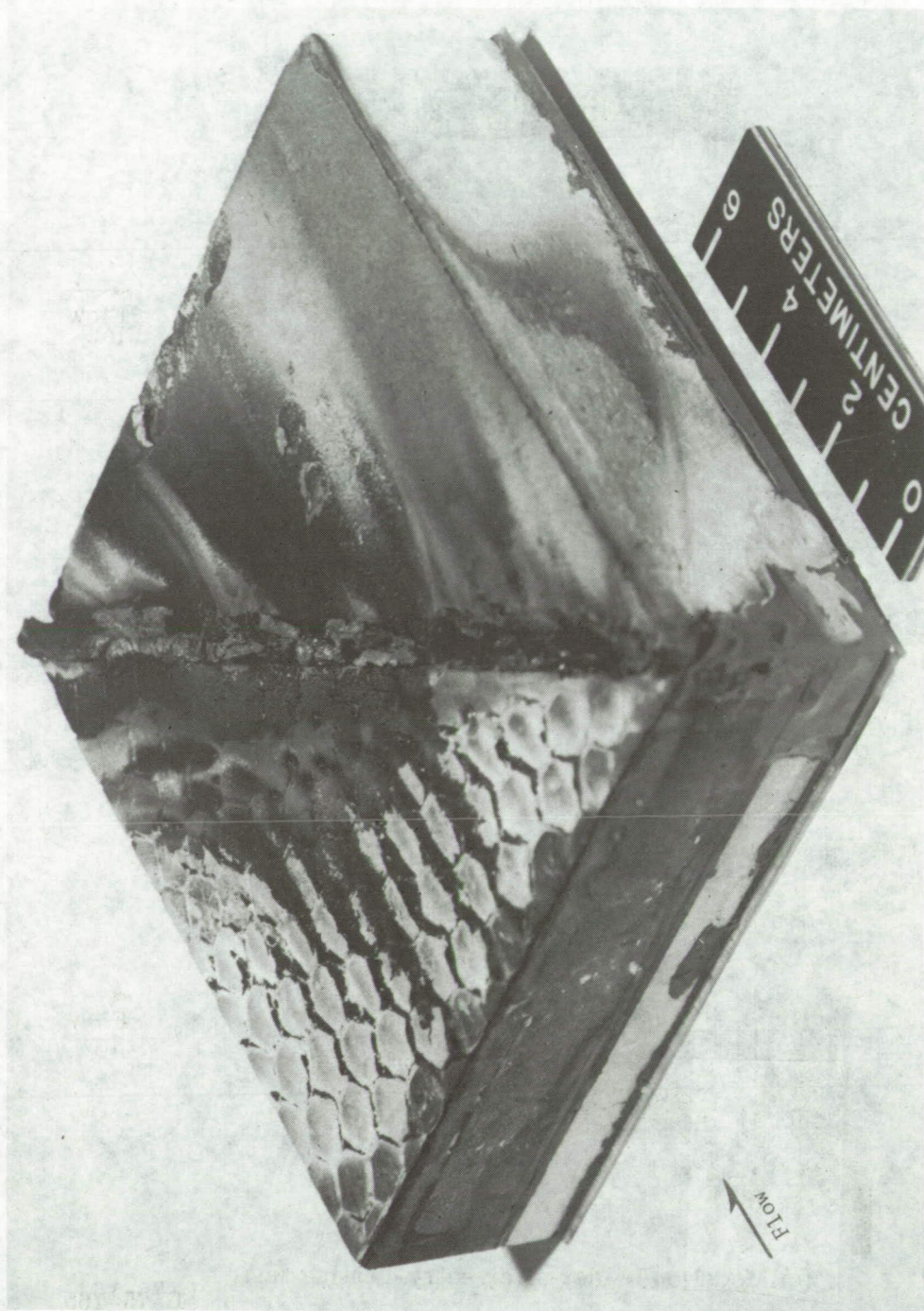


(a) Model on holder before entry-heating test.



(b) Model on holder after entry-heating test. L-75-163

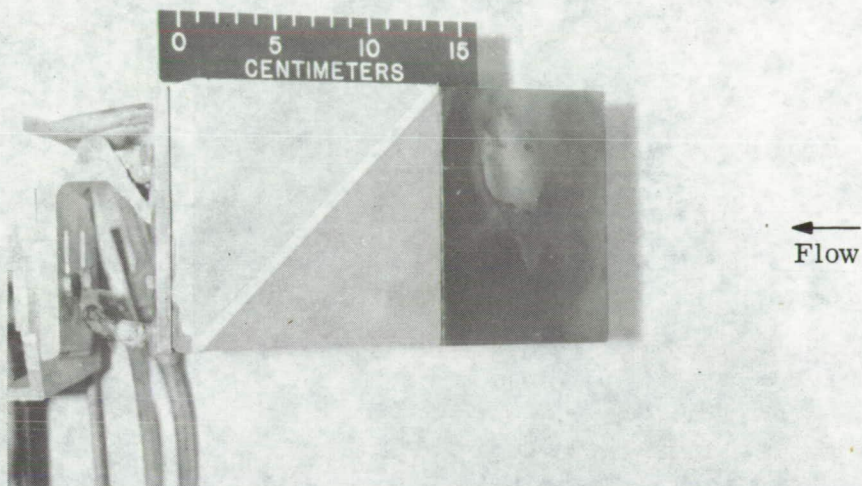
Figure 18.- Spanwise-joint model with a wavy silicone-rubber seal.



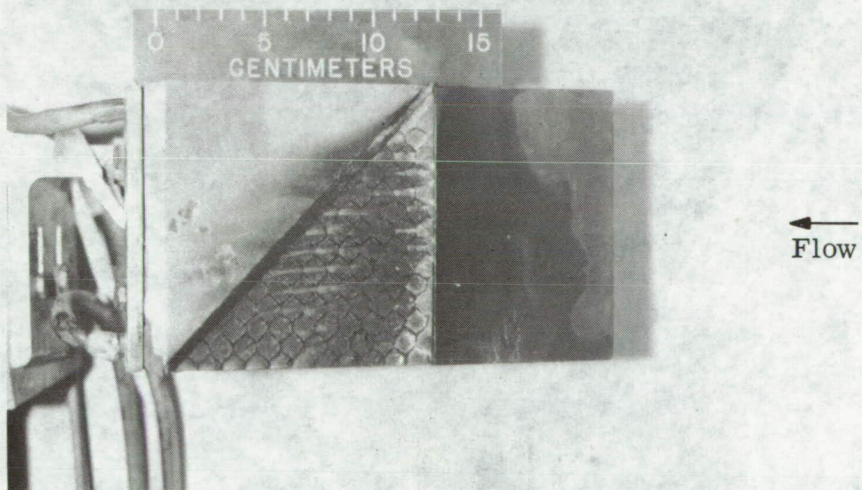
L-75-164

(c) Closeup of tested model.

Figure 18.- Concluded.



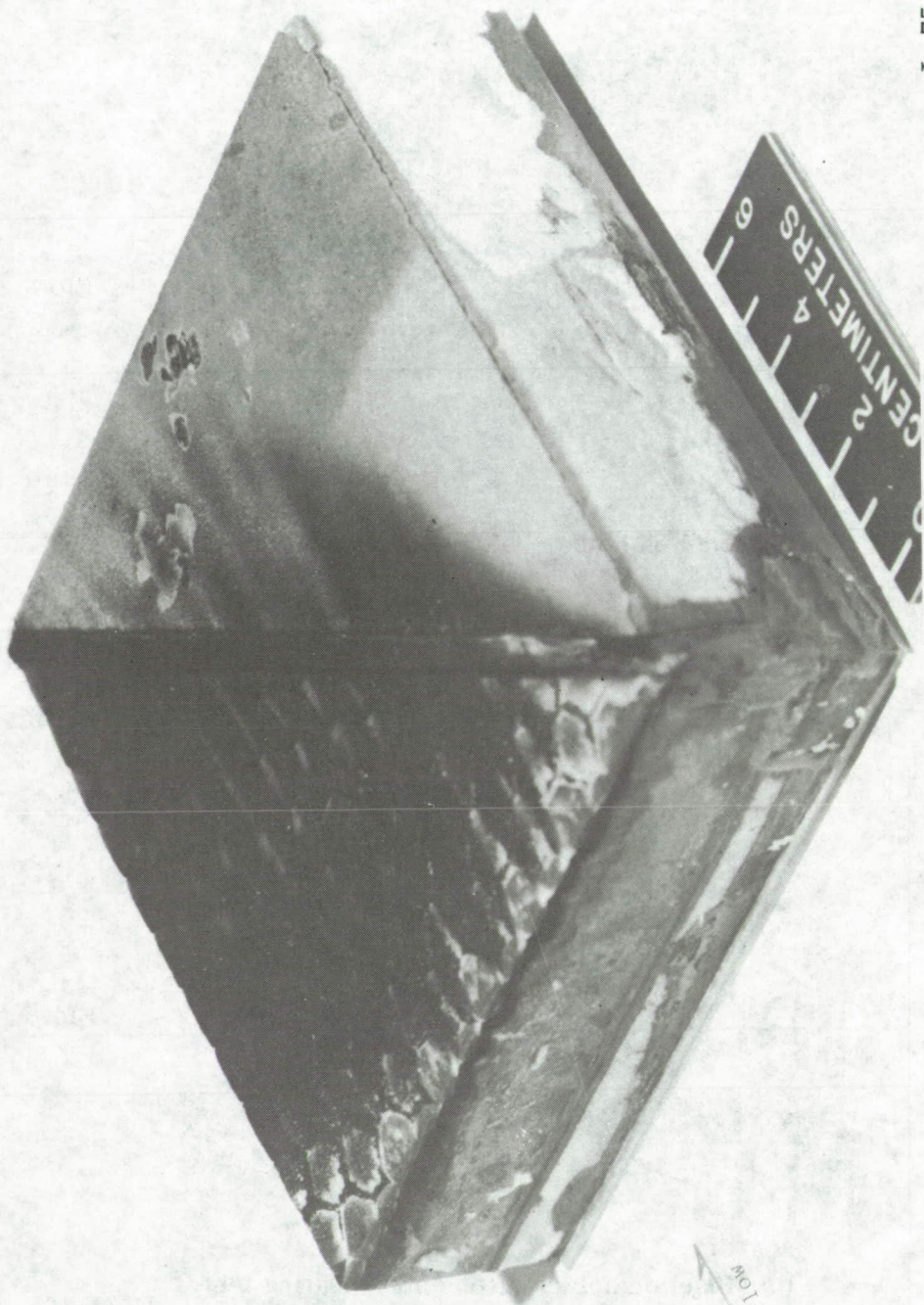
(a) Model on holder before entry-heating test.



(b) Model on holder after entry-heating test.

L-75-165

Figure 19.- Spanwise-joint model with a silica-felt seal.



L-75-166

(c) Closeup of tested model.

Figure 19.- Concluded.



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